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OPTIMIZATION OF WATER-JET PROPULSION SYSTEM FOR SURFACE EFFECT SHIPS

William Raymond Johanek

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OPTIMIZATION OF WATER-JET PROPULSION SYSTEM
FOR SURFACE EFFECT SHIPS

by

WILLIAM RAYMOND JOHANEK

B.S., U.S. COAST GUARD ACADEMY (1968)

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE
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AND MASTER OF SCIENCE
IN MECHANICAL ENGINEERING

at the

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MAY, 1974

Thesis

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OPTIMIZATION OF WATER-JET PROPULSION SYSTEM FOR SURFACE EFFECT SHIPS

by

William Raymond Johanek

Submitted to the Department of Ocean Engineering on May 9, 1974, in partial fulfullment of the requirements for degrees of Master of Science in Naval Architecture and Marine Engineering and Master of Science in Mechanical Engineering.

ABSTRACT

Water-jet propulsion systems using flush inlet suitable for use on surface effect ships are studied. The equations governing the performance of the system are developed and incorporated into a computer program which optimizes the system on a least total weight basis. Resistance, displacement, range, speed, and other data are supplied to the program which then calculates total propulsion system weight for a number of jet velocity ratios. The system utilizes marine gas turbine engines coupled to multi-stage axial-flow pumps through planetary reduction gears. Variable area flush inlets and constant area nozzles are used. Results for a 2000 ton vessel are presented and show the influence of the jet velocity ratio on the weight and power requirements of the vessel. A FORTRAN computer program listing is included.

Thesis Supervisor: A. Douglas Carmichael

Title: Professor of Power Engineering

TABLE OF CONTENTS

Title Page..1

Abstract..2

Table of Contents 3

List of Figures and Tables....................................4

List of Symbols Used in Text..................................5

Chapter 1. Introduction.......................................8

Chapter 2. System Description................................11

Chapter 3. Development of Equations..........................14

Chapter 4. Pumps, Reduction Gears, and Engines...............21

4.1 Pumps..21

4.2 Reduction Gears..27

4.3 Engines 29

Chapter 5. Results...31

Chapter 6. Conclusions and Recommendations...................33

Bibliography...35

Figures..37

Tables...50

Appendix A. Additional Inlet Data............................52

Appendix B. Sample Calculation...............................54

Appendix C. Computer Program Description and User's Guide....60

List of Program Variables....................................63

Program Listing..70

LIST OF FIGURES

Figure No.	Title	Page
1	General configuration of an SES	37
2	Variation of drag with vessel speed and lift to drag ratio for surface effect ships	38
3	Propulsion system arrangement	39
4	Inlet drag coefficient for varying aspect ratio inlets	40
5	Design speed overall internal efficiency for varying aspect ratio inlets	41
6	Hump speed overall internal efficiency varying aspect ratio inlets	42
7	Total inlet system weight coefficients for varying aspect ratio inlets	43
8	Hump speed overall internal efficiency for 2.5 aspect ratio inlets	44
9	Total inlet system weight coefficient for 2.5 aspect ratio inlets	45
10	Design speed overall internal efficiency for 2.5 aspect ratio inlets	46
11	Inlet drag coefficient for 2.5 aspect ratio inlets	47
12	Variations of propulsive coefficient with jet velocity ratio	48
13	Correlation of Dudley's method of estimating reduction gear weight	49

LIST OF TABLES

1	COMPUTER PROGRAM OUTPUT FOR JET VELOCITY RATIO =1.946	50
2	COMPUTER OUTPUT FOR VARIOUS JET VELOCITY RATIOS	51

SYMBOLS USED IN TEXT

A_j	-	Jet area	ft^2
A_p	-	Pump inlet area	ft^2
C	-	Ratio of entering water's momentum velocity to ship's velocity V_m/V_o	
C_A	-	Acceleration coefficient	
C_b	-	Pump blockage coefficient	
C_D	-	Inlet drag coefficient	
C_L	-	Pump length coefficient pump length over pump inlet diameter	
C_w	-	Weight coefficient used for both inlet and pump	
D	-	Inlet system drag	lb
g	-	Acceleration due to gravity	ft/sec^2
h	-	Difference in height between outside waterline and diffuser exit	ft
Ha	-	Atmospheric pressure head	ft
he	-	Height of diffuser exit above inlet	ft
$h_{l\,ep}$	-	Head loss between diffuser exit and pump inlet	ft
h_p	-	Height of pump above inlet	ft
H_p	-	Change of head across pump	ft
H_{p1}	-	Head at enterance to pump	ft
h_{p2}	-	Head at pump exit	
H_2	-	Heat at diffuser exit	ft
Hsv	-	Net positive suction head	ft

HP_p	- Horsepower delivered to the water	horsepower
K	- K-factor of reduction gear	
L_p	- Length of pump	ft
r_g	- Reduction gear ratio	
n_p	- Reduction gear input pinion RPM (ie engine RPM)	RPM
N_s	- Suction specific speed	$\frac{RPM(gal/min)^{.5}}{ft^{.75}}$
p_v	- Vapor pressure of water	ft
PC	- Propulsive coefficient	
Q	- Flow rate	ft^3/sec
	- Reduction gear Q-factor	
R	- Ship's resistance	lb
r_h	- Pump hub radius	ft
r_h/r_t	- Ratio of pump hub radius to blade tip radius	
r_t	- Pump blade tip radius	ft
RPM	- Pump or engine RPM	RPM
SFC	- Specific fuel consumption	lb/HP-hr.
SHP	- Required engine power output	horsepower
T	- Thrust	lb
t	- Time interval	hr
U_t	- Blade tip velocity	ft/sec
V_j	- Jet velocity	ft/sec
V_j/V_o	- Jet velocity ratio	
V_m	- Momentum velocity of entering water	ft/sec
V_o	- Ship's speed	ft/sec

V_z	- Velocity of water entering pump	ft/sec
W_d	- Pump weight	
W	- Weight of inlet system	lb
W_g	- Reduction gear weight	lb
W_w	- Weight of water in pump	lb
	- Density of water	$\frac{slug/ft^4}{sec^2}$
ϕ	- Pump flow coefficient	
ψ	- Pump head coefficient	
π	- Pi	
η_g	- Gear efficiency	
η_n	- Nozzle efficiency	
η_{OA}	- Inlet system overall internal efficiency	
η_{OA}'	- Inlet system overall internal efficiency (uncorrected for height)	
η_p	- Pump efficieny	

1. INTRODUCTION

Vessels wholly or partially supported by a cushion of air are described as "surface effect ships". Recently, this term has evolved through usage to the point where it is used when refering to rigid sidewall captured air bubble vehicles, while vessels with flexible sidewalls are termed "air cushion vehicles". The rigid sidewalls together with flexible end seals enclose the air cushion on the SES. Most of the vessel's weight is supported on this cushion with the air being supplied by lift fans. The general configuration of the SES may be seen in figure 1.

By lifting the vessel's hull partially out of the water on an air cushion the resistance of the vessel is greatly reduced and the craft can be operated at high speeds with reasonable power requirements. There is no one typical drag versus speed curve for surface effect ships as the resistance depends on many factors including length to beam ratio, cushion pressure, sidewall length, sidewall width, and the amount of the frontal area. The effect of varying the length to beam ratio can be seen in figure 2. In general, it can be said that surface effect ships have lower resistances than conventional vessels and in many cases they have lower resistances than hydrofoils. The high length to beam ratio SES has a lower drag over a wide range as shown in figure 2. Thus a high length to beam ratio SES might be used for vessels operating at speeds between 35 and 60 knots and lower length

to beam ratio ships would be used for operations above this.

One of the major problems with surface effect ships is their propulsion systems. Operating at speeds over about 60 knots eliminated the possible use of conventional propellers due to cavitation. Air propellers, although efficient, take up much deck space and present a personnel hazard. In addition, they are not very efficient at low speeds and their weight is high. Supercavitating propellers can be efficient but they are noisy, they vibrate, and their operation in a seaway is uncertain. Water-jet propulsion systems are not very efficient but relatively simple, reliable, and flexible. The pumps, gears, and engines may be placed higher in the ship eliminating the need to widen the sidewalls. Thus the vessel's drag can be kept low. In addition to their poor efficiency, the weight of the waterjet system is a drawback. The water in the system is a significant factor in this weight.

The subject of this paper is the water-jet propulsion system for surface effect ships. The emphasis is on the weight and efficiency of the system. The final objective of this thesis was to develop a computer program which would select the optimum system for a given SES. The selection procedure for the system is based on least total weight including the fuel required for a given endurance. Specifically, the study was done for the U. S. Navy's contemplated 2000 ton 80 knot SES but the resulting program may be used for a number of different vessels. Previous studies have been made on water-

jet systems for hydrofoils (see references 2,3, and 4) and much of the information contained in the previous studies was used for the pump and engine segments of the program. The concentration in this paper is on the flush inlet system which may be used for the surface effect ships and is not applicable to the hydrofoil.

2. SYSTEM DESCRIPTION

The water-jet propulsion system for a SES is made up of eight components: the inlet opening and associated fairing, a movable ramp, the diffuser, the pump, the reduction gear, the engine, the nozzle, and necessary piping, as shown in figure 3. The inlet is described as being flush since it lies in the same plane as the bottom of the hull. The primary concern here is to minimize drag while bringing the water into the hull. The curvature of the leading edge and the raduis of the lip are important parameters in this respect. To prevent separation of the flow the leading edge curvature must not be too sharp. At the same time, too shallow a bend results in heavier systems. The lip radius should be made as small as possible to minimize drag but is constrained by several factors. Cavitation prevention, debris damage resistance, and the possible need to place sensors near the lip put lower limits on the lip size. The inlet ratio (the ratio of the inlet width to inlet height) also effects drag. With low aspect ratios having lower drag. At the same time, the smaller aspect ratio inlets may require longer and heavier transition sections after the diffuser.

The movable ramp opens the inlet at low speeds to allow more flow through the system. The variation of area depends on the drag characteristics of the vessel, the operating speed, the jet velocity ratio, and other factors. In the 2000 ton vessel example, the power requirements at hump speed and at

cruise are nearly the same, and the required flow rate of water is nearly the same. Thus, the ratio of the inlet area at hump to area at cruise should be about equal to the ratio of the ship's velocity at cruise to the velocity at hump.

The diffuser, downstream of the flush inlet, slows the flow down to prevent cavitation at the pump. Diffuser design is crucial to the system. On one hand a shallow diffuser angle is desired to minimize losses and on the other a shallow angle increases the diffuser length and consequently the weight of the system. Appendix A gives data for the diffuser used in the study. Additional information on the inlet, diffuser, and other design aspects of the system can be found in reference 1.

The pump used in the study consists of an inducer stage followed by one or more axial stages. The flow coefficient of the inducer stage was set at 0.15 to give diffuser ratios similar to those for which data was available in reference 1. It was further assumed that there would be one engine per pump and that all engines and pumps would be identical. Since it was assumed that each engine would drive a single pump and because of their light weight, planetary reduction gears would be used. Further details of pumps, gears, and engines will be presented in chapter 4.

The nozzles and additional piping of the system is not considered in detail in the program. Provision for their weights is made but other than allowing for an assumed nozzle

efficiency and the difference in height between the diffuser outlet and the pump, the head losses are ignored as being small compared to the remainder of the system.

3. DEVELOPMENT OF EQUATIONS

A waterjet propulsion system produces thrust by increasing the momentum of the ingested water. Thus the thrust developed is given by:

$$T = \rho Q(V_j - V_m) \tag{3.1}$$

or, defining $C = V_m/V_o$

$$T = \rho Q(V_j/V_o - C)V_o \tag{3.2}$$

In steady state the thrust must equal the total resistance of the ship which is the resistance of the hull plus the drag caused by the propulsion system. Or,

$$T = R + D \tag{3.3}$$

Reference 1 gives the drag of the inlet system in terms of a drag coefficient, C_D. Thus,

$$D = C_D Q V_o \rho/2 \tag{3.4}$$

Figure 4 shows the drag coefficient versus speed curves for varying aspect ratio inlets.

Combining 3.2, 3.3, and 3.4 yields

$$\rho Q(V_j/V_o - C)V_o = R + C_D Q V_o \rho/2 \tag{3.5}$$

When the vessel is accelerating (such as over the hump region) the thrust must be greater than the total resistance. Or, letting C_A be the acceleration coefficient, 3.5 becomes:

$$\rho Q(V_j/V_o - C)V_o = C_A\ (R + C_D Q V_o \rho/2) \tag{3.6}$$

Where $C_A > 1$. Equation 3.6 can then be solved for Q.

$$Q = C_A R/\rho V_o \ (V_j/V_o - C - C_A C_D/2) \qquad (3.7)$$

Since the power delivered to the water is given by:

$$HP_p = H_p Q \rho g/550 \qquad (3.8)$$

and Q is given by equation 3.7, only an expression for H_p, the head across the pump is needed.

Reference 1 defines the overall internal efficiency of the system (η_{OA}) as a measure of the head recovery between the inlet and the diffuser outlet. Figures 5 and 6 show $\eta_{OA'}$ versus vessel speed for the varying aspect ratio inlets. These curves are η_{OA} for infinite Froude number or diffusers whose exits lie in the same plane as their inlets. In the actual case, these efficiencies must be corrected for the change in elevation between inlet and outlet. The corrected efficiency is:

$$\eta_{OA} = \eta_{OA'} - h/V_m^2/2g. \qquad (3.9)$$

Therefore, the total head at the diffuser outlet is:

$$H_2 = \eta_{OA} V_m^2/2g \qquad (3.10)$$

and the head at the entrance to the pump is:

$$H_{p1} = h_p - h_e + H_2 - h_{lep} \qquad (3.11)$$

Assuming that the nozzle is at the same elevation as the pump and ignoring the nozzle efficiency, the head at the

exit of the pump is:

$$H_{p2} = V_j^2/2g \qquad (3.12)$$

Equations 3.10, 3.11, and 3.12 can be combined to get the head rise across the pump.

$$H_p = V_j^2/2g - \eta_{OA} V_m^2/2g + h_p - h_e + h_{lep} \qquad (3.13)$$

Making the assumption that h_{lep} (the loss between the diffuser outlet and the pump entrance) is small compared to the other terms and letting $h_p - h_e$ be h, 3.13 becomes:

$$H_p = ((V_j/V_o)^2 - C^2 \eta_{OA})\, V_o^2/2g + h \qquad (3.14)$$

and substituting 3.7 and 3.14 into 3.8 gives

$$HP_p = \frac{C_A R V_o \; ((V_j/V_o)^2 - C^2 \eta_{OA} + 2hg/V_o^2)}{(550)\;(2)\;(V_j/V_o - C - C_A C_D/2)} \qquad (3.15)$$

The shaft horsepower required is then:

$$SHP = HP_p/\eta_p \eta_g \eta_n \qquad (3.16)$$

The propulsive coefficient is defined as the thrust divided by the shaft horsepower. Incorporating the gear and nozzle efficiencies into the pump efficiency PC becomes:

$$PC = \frac{2 \;{}_p(V_j/V_o - C - C_A C_D/2 + C_A C_D/\,(2V_o))}{((V_j/V_o)^2 - C^2 \eta_{OA} + 2hg/V_o^2)} \qquad (3.17)$$

By taking the derivatives of 3.15 and 3.17 with respect to

V_j/V_o and setting the results equal to zero expressions can be found for the velocity ratios for which the required horsepower is minimum and the propulsive coefficient is maximum. These are :

$$V_j/V_o = C + C_A C_D/2 + (C + C_A C_D/2)^2 - C^2 \eta_{OA} + 2hg/V_o^2 \qquad (3.18)$$

for minimum power and

$$V_j/V_o = C + C_A C_D/2 - C_A C_D/2V_o + (C + C_A C_D/2 - C_A C_D/2V_o)^2 - C^2 \eta_{OA} + 2hg/V_o^2 \qquad (3.19)$$

for maximum PC. Because of the definition of PC the minimum power does not occur at the maximum PC. The two velocity ratios are close enough, however, that either can be used in connection with equation 3.15 to estimate the power required by the SES.

As shown below, the problem is not as simple as just using these equations to predict requirements. Once a jet velocity ratio at cruise is selected from equation 3.18 or 3.19 the flow rate through the system is determined from equation 3.7 and the area of the jet is:

$$A_j = Q/(V_o(V_j/V_o)) \qquad (3.20)$$

Then using a constant area jet, Q equals the jet area times

the jet velocity and equation 3.6 can be used to solve for the jet velocity ratio at hump.

$$(V_j/V_o) \text{ Hump} = .5C + C_A C_D/4 + (.5C + C_A C_D/4)^2 + C_A R/(\rho A_j V_o^2) \qquad (3.21)$$

Where all terms are at the hump speed. The jet velocity ratio is then used to determine the flow rate, head rise across the pump and the horsepower required by use of equations 3.7, 3.8, and 3.15 respectively. The use of a constant area jet links the two velocity ratios together and it is possible that by using the power optimum jet velocity ratio at cruise will result in a velocity ratio at hump which is far from the power optimum at hump. In fact, with a given set of conditions there may be no possible jet velocity ratio, at which the ship is both able to accelerate over the hump and able to cruise at the desired speed. In this case, either the cruise speed or the acceleration margin would have to be reduced or larger or more engines would have to be used. Appendix B presents a sample calculation using the above equations and figure 12 shows the variation of propulsion coefficient with jet velocity ratio and the range of velocity ratios which may be used for this example.

The weight of the inlet system including the water up to the diffuser outlet is given in reference 1 as:

$$W = C_w Q^{1.5} \qquad (3.22)$$

Values of C_w versus speed are shown in figure 7 for the varying aspect ratio inlets. The weight given by equation 3.22 represents the total weight of the system including structure, ducting, and water. Additional ducting such as the transition pipe, pump elbow, and nozzle pipe are not included. As can be seen from equation 3.7 the flow rate decreases with increasing jet velocity ratio. Thus the weight of the inlet system will decrease with increasing velocity ratio. Since the propulsive coefficient versus velocity ratio curve is relatively flat for high velocity ratios it should be anticipated that the lightest system will have a high jet velocity ratio.

As was mentioned previously , the aspect ratio is the ratio of the inlet width to the inlet height. As used here the term "varying aspect ratio" inlets means those with aspect ratios equal to the sytem's diffusion ratio. Other inlets are termed "fixed aspect ratio" inlets. The varying aspect ratio inlets in general are more efficient and lighter. The movable ramp is greatly simplified by using diffusion ratios equal to the inlet aspect ratios. The area is varied by moving the roof of the inlet. Thus, in general it is desirable to use the varying aspect ratio inlets. In some cases, this will not be possible due to sidehull width constraints. That is, using an aspect ratio equal to the diffusion ratio could result in an inlet width which would be

as wide or wider than the hull. In these cases smaller aspect ratios must be used. Reference 1 presents data on 2.5 aspect ratio inlets and it is repeated in figures 8, 9, 10, and 11.

4. PUMPS, REDUCTION GEARS AND ENGINES

4.1 PUMPS

The pumps considered for use in SES water-jet propulsion systems are centrifugal and axial flow pumps. Since the available data on the inlet system is for systems of 10,000 to 40,000 horsepower and the head rise, flow rate, and suction specific speeds required in the system are all high, it appears that axial flow pumps are better suited for this application. Previous comparisons of axial flow and centrifugal pumps in water-jet systems (ref. 2) having nearly the same requirements show that the centrifugal pumps are usually much heavier and their placement in the system is much more complicated. Generally multi-parallel stages are required and the associated gearing, shafting, and ducting is complicated and heavy. Centrifugal pumps are, therefore, not considered in this paper.

Two factors affected the choice of axial flow pumps used in this system. First, the data presented in reference 1 was based on a specific pump. This was a pump whose inlet flow coefficient is 0.15 and could operate at suction specific speeds of up to 16,000. Because the system's diffusion ratio depends on the pump flow coefficient and the inlet system data was presented for specific diffusion ratios; the use of 0.15 for the flow coefficient was dictated. The suction specific speed is the second factor. Although pumps have been built and operated at suction specific speeds as high as

26,000 it was decided to limit the pumps in this system to 16,000, as being more reasonable. The pump assumed in the calculation procedure is constrained to operate below a specific speed of 16,000.

The above limit does not guarantee that the pump will be cavitation free at hump speeds. Reference 5 presents data on a pump operated up to a suction specific speed of 26,000. It points out that although the pump had good preformance characteristics up to this speed, cavitation was present at about a suction specific speed of about 3,800. Cavitation normally occurs first on the inducer stage. In general, however, the inducer still produces enough head rise to keep the remaining stages from cavitating. Thus, when more than one stage is used the performance of the pump is not greatly effected by cavitation on the inducer stage. It is therefore indicated that the pump may very well cavitate while the vessel is accelerating, but that there should be no major loss in performance.

Besides loss of pump performance in a cavitating regime possible pump damage must be considered. This damage depends both on the extent of cavitation and on the length of time the pump is operated in this consition. More extensive test data on pump deterioration is desirable. A study on the dynamics of a surface effect ship using a water-jet propulsion system was undertaken by Bruce (reference 6) and shows the acceleration characteristics of the vessel. Although his results

show a long acceleration period before the vessel reached cruise speed (about 4 minutes), the period of time spent in the hump region is quite short (about .5 minutes). This suggests that some cavitation can be tolerated.

Using high suction specific speeds leads to high pump speeds (RPM). Consequently, small reduction ratios are needed and weight is saved in the reduction gears. The RPM is limited indirectly by the maximum allowable blade tip speed. In this instance, the maximum tip speed is limited to 200 feet per second.

The head coefficients for the pump were set at 0.41 for the inducer and 0.3 for the following stages. In an actual pump design, the inlet flow coefficient and the head coefficients cannot be simply arbitrarily selected. Pumps have been built which have coefficients approximately equal to these so they are considered reasonable even though they may not be the optimum for all designs. Since the methods of estimating the weight of pumps do not correspond very well to weights of produced pumps, using slightly different coefficients to estimate the pump size should induce very little additional error in the total system weight . Users of this program should be cautioned to ensure that their particular pump requirements are reasonably satisfied by the pump design used here.

Knowing the flow rate and head rise through the pump from equations 3.7 and 3.13 the pump design proceeds as follows. The flow coefficient relates the axial velocity

of the entering water to the blade tip velocity.

$$\phi = V_z/U_t \qquad (4.1.1)$$

and the head rise coefficient relates the head rise across the pump to the blade tip velocity.

$$\Psi = gH_p/U_t^2 \qquad (4.1.2)$$

using equation 4.1.1 with $\phi = .15$ and U_t equal to its maximum permissable value of 200 ft/sec, V_z is found and then r_t is found by:

$$r_t = Q/V_z\pi(1 - (r_h/r_t)^2 \qquad (4.1.3)$$

Since the inlet area of the pump is $\pi(r_t^2 - r_h^2)$. Knowing r_t and U_t sets the pump RPM (RPM = 30 $U_t/\pi r_t$). The suction specific speed is then calculated by:

$$N_s = \text{RPM } Q^{.5}/H_{sv}^{.75} \qquad (4.1.4)$$

Where Q is in gallons/minute and H_{sv} is the net positive suction head

$$H_{sv} = H_a + H_{p1} - p_v \qquad (4.1.5)$$

If N_s exceeds 16,000 the tip velocity is reduced and r_t, RPM, and N_s are recalculated until N_s is equal to or less than 16,000.

The efficiency of the pump at the design speed is assumed to be 91.5% for a pump whose diameter is 3.66 feets. This is the same at what is used in reference 2. As in reference 2,

a Reynolds Number correction is applied for the actual pump diameter to determine the pump efficiency. This efficiency is then used to find the propulsive coefficient at hump speed and the required shaft horsepower is calculated and compared to the available SHP. If the required SHP is less than or equal to the available power the vessel will be able to accelerate over the hump (the acceleration coefficient is included in the required power) and the design may be continued. If not, the pump blade tip speed can be reduced. This increases the pump diameter and, therefore, the efficiency. It also encreases the head coefficient of the pump according to equation 4.1.2. The number of stages is determined from the resulting head coefficient. That is, the inducer is allowed a head coefficient of 0.41 and each subsquent stage 0.30.

The off design point pump RPM and efficiency are found in the same manner as presented in references 2 and 3. That is, the pump head, efficiency and RPM characteristics are assumed parabolic. The coefficients used are the same as those in reference 2 and the characteristics for two or three stage pumps are assumed to be identical. After finding the efficiency and RPM at the cruise speed, the propulsion coefficient, required power and blade tip speed are found. The required power is compared to available power and the blade tip speed is checked against the 200 ft/sec limit. If either of the above are unacceptable, the blade tip speed at the hump speed is decreased and the entire procedure is

repeated. The pump dry weight is calculated by the equation:

$$W_d = C_w D^{2.3} \qquad (4.1.6)$$

and the weight of the water in the pump by:

$$W_w = C_b A_p L_p \rho g \qquad (4.1.7)$$

Where C_b is a blockage coefficient and L_p, the pump length is given by:

$$L_p = C_L D \qquad (4.1.8)$$

In general, increasing the pump diameter or decreasing the blade tip speed increases the pump efficiency slightly and greatly increases the pump weight.

4.2 REDUCTION GEARS

It is assumed that planetary reduction gears will be used in these systems. Since the LM 2500 gas turbine which is being considered for use on the United States Navy's 2000 ton SES puts out a maximum of 22,500 shaft horsepower the gears must be capable of transmitting this. The feasibility of planetary gears of this size has been demonstrated by a 40,000 SHP gear built by Curtiss-Wright.

The weight of the reduction gear is estimated using the Dudley method. The weights obtained from this method correlate well with existing gears. Two factors (K and Q) are used in the method. An important portion of the tooth stress is proportional to the square root of the gear's K-factor. The range of K-factors which are reasonable for use on surface effect ships is between 400 and 800.

The second factor, Q, is defined as:

$$Q = HP\,(m_g + 1)^3 / n_p m_g \qquad (4.2.1)$$

Where m_g is the reduction ratio, n_p is the speed of the input pinion in RPM and HP is the shaft horsepower. In effect, this definition relates the gear's required geometry to the weight. The resulting weight equation for planetary gears is:

$$W_g = 9500\ Q/K \qquad (4.2.2)$$

Figure 13 shows the weight correlation for a limited number of gears. The weights given by 4.2.2 include the gear, casing,

oil reservoir, oil pump, and stub shaft but not the oil or necessary foundation.

4.3. ENGINES

Gas turbine engines designed for or modified for marine use may be employed in water-jet systems. Although high speed diesels may be used, in general they are heavier and have not been considered. This may not be a valid assumption in all circumstances when the total system is considered. Some gas turbines have very poor specific fuel consumptions and the added weight of required fuel may offset the engine weight saved by using the lighter weight turbine. The twelve engines used in references 2 and 3 are again used here with the same characteristics. That is, normal SHP, maximum SHP, specific fuel consumption, shaft RPM, and engine dry weight are inputs to the program. As in references 2 and 3 the specific fuel consumption is assumed to vary with the ratio of SHP to normal SHP raised to a power, n. The value of the power, n, changes when this power ratio is 0.7. Since the pump RPMs at cruise and hump speed are determined by the pump design as are the power requirements, it is assumed that the engine can develop the required power at the corresponding shaft speeds. No consideration of the engine's power versus RPM characteristics is made. These assumptions may not be valid for all engines or all operating ranges and once again the user is cautioned.

The fuel consumption is found by dividing the endurance time into steps. The fuel required for each step is:

$$W_f = (SFC)\ (SHP)\ (t) \tag{4.3.1}$$

When the weight for one time period is found, it is subtracted from the vessels weight and the resistance of the vessel is recalculated using a constant lift to drag ratio. The resistance of an actual SES will not vary in this way but will decrease as weight is removed (L/D will not be constant. Reference 7). To show some decrease in resistance and because of the fact that the weight of the fuel used by the lift fans is ignored in the program, the above assumption seems reasonable. Accounting accurately for the lift fan fuel and the decreasing resistance of the vessel would be possible but extremely complicated. On the other hand, since the fuel makes up a substantial amount of the total ship weight its expenditure is significant.

Since the jet area is fixed, $Q = V_j A_j$ and equation 3 becomes:

$$A_j \rho (V_j^2 - V_m V_j) = R + C_D \rho A_j V_j V_o / 2 \qquad (4.3.2)$$

and can be solved for V_j. R is the new resistance after the fuel is removed. Then assuming the pump efficiency remains constant, the shaft horsepower required is:

$$SHP = \frac{g A_j V_j \ (V_j^2/2g - V_m^2 \eta_{OA}/2g - h)}{550 \ \eta_p \eta_g \eta_n} \qquad (4.3.3)$$

The fuel required for the next time interval is calculated using this horsepower.

5. RESULTS

Table 1 is output from the computer program for the 2000 ton 80 knot test case and for jet velocity ratio equal to 1.9463. Table 2 shows a summary of data for the same vessel and a variety of jet velocity ratios.

In the weight summary it should be noted that the inlet system and the fuel (1000 mile range) make up 86.7% of the total system weight. In addition, the inlet system's drag makes up about 7% of the total resistance. In this run the pumps were assumed to be at the same height as the diffuser outlet and, therefore, the additional water weight is zero. Based on the assumptions in chapter 4, the transition pipe would add about 3,130 pounds of water for each foot which the pump is elevated above the diffuser outlet. Therefore, even a 10 foot difference would have little effect on the total weight. Since the engine (LM2500) used in this case has an excellant specific fuel consumption (.41 at normal horsepower), the fuel weight represents a minimum weight. It is doubtful that any significant saving in weight could be made by using high speed diesel engines or any other turbine.

The pump flow rates at cruise and hump speeds are nearly identical as are the pump heads. This results in nearly equal efficiencies at the two conditions. The pump runs only about 40 RPM slower at cruise speed than at hump speed and because of the high pump speed (about 1200 RPM) a reduction gear ratio of only 2.79 is required. The resulting reduction

gear is lightweight. The required engine speed and horsepower changes between hump speed and cruise speed correspond well with the engine's performance characteristics.

The inlet data shows that the movable ramp must move about 1.72 feet to admit the necessary flow at hump speed. This seems reasonable. It should also be noted that the width of the inlet is 4.17 feet. This should cause no problems in the design of the sidehulls. The required diffusion ratio is 4.0164 and the data used in the program was based on a diffusion ratio of 4 for an 80 knot ship.

The summary of data for various jet velocity ratios (table 2) dramatizes the affect which the velocity ratio has on the weight ratio, propulsive coefficient, and power requirements. The maximum propulsive coefficient occurs at velocity ratio equal to 1.8263 as does minimum cruise horsepower. According to equation 3.19 the propulsive coefficient should be maximum at jet velocity ratio equal to 1.8063. In the developement of equation 3.19 it was assumed that the pump efficiency is independent of jet velocity ratio. In the program the pump efficiency is dependent on the velocity ratio and as a result the maximum propulsive coefficient occurs at a higher velocity ratio.

6. CONCLUSIONS AND RECOMMENDATIONS

The high weight of the water-jet propulsion system is a drawback to its use. The water in the system and the required fuel make up the largest portion of the weight. As can be seen from the results presented previously, using a higher jet velocity ratio reduces the weight of the system without seriously affecting the overall propulsive coefficient. In most cases it appears that to obtain the least weight system the velocity ratio should be set at its highest possible value. This limit occurs when the power required to accelerate or cruise exceeds the available power.

The low efficiency of the system contributes to the high weight of fuel. Only about 7% of the total drag of the vessel is due to the inlet system. Although it may be possible to reduce this through the use of a better design, little saving of weight would be achieved. An increase in the overall internal efficiency of the diffuser will result in a lighter system. However, a 10% increase in the internal efficiency will result in less than a 1% increase in the propulsive coefficient and thus reduce the system's weight.

In summary, it appears that although some improvements may be made in the flush inlet water-jet system, the saving in weight will be small. The drag of the inlet, the internal efficiency of the diffuser, and the pump efficiency may be improved. The drag is already low and the efficiencies are high, so little improvement should be expected.

More experimental data on inlets and diffusers is needed. As is more data on axial flow pumps. This data should then be incorporated into the computer program. It is also recommended that the weight of the lift fans and their required fuel also be added to the program, along with a more accurate method of predicting the variation of drag as weight is removed. An arrangement feasability study is also needed. The effects of splitting the flow between the pumps should be included in this.

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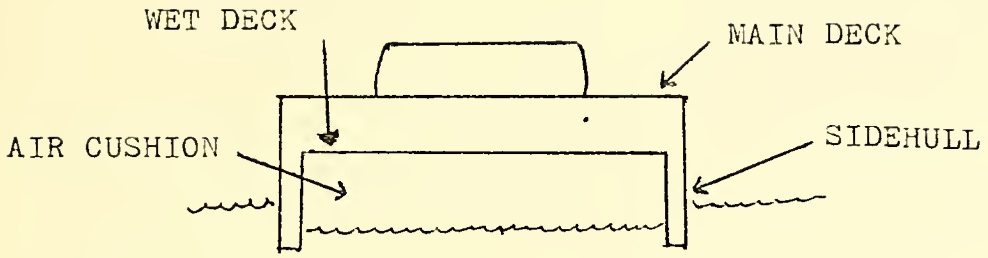
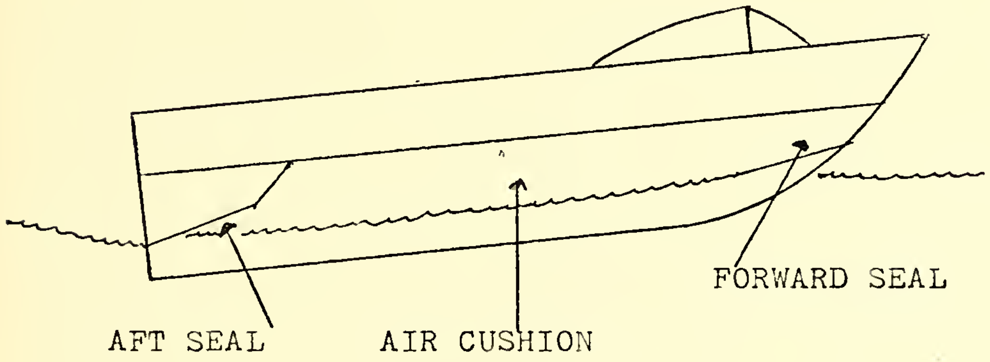


FRONT VIEW



SIDE VIEW

Figure 1 - GENERAL CONFIGURATION OF AN SES

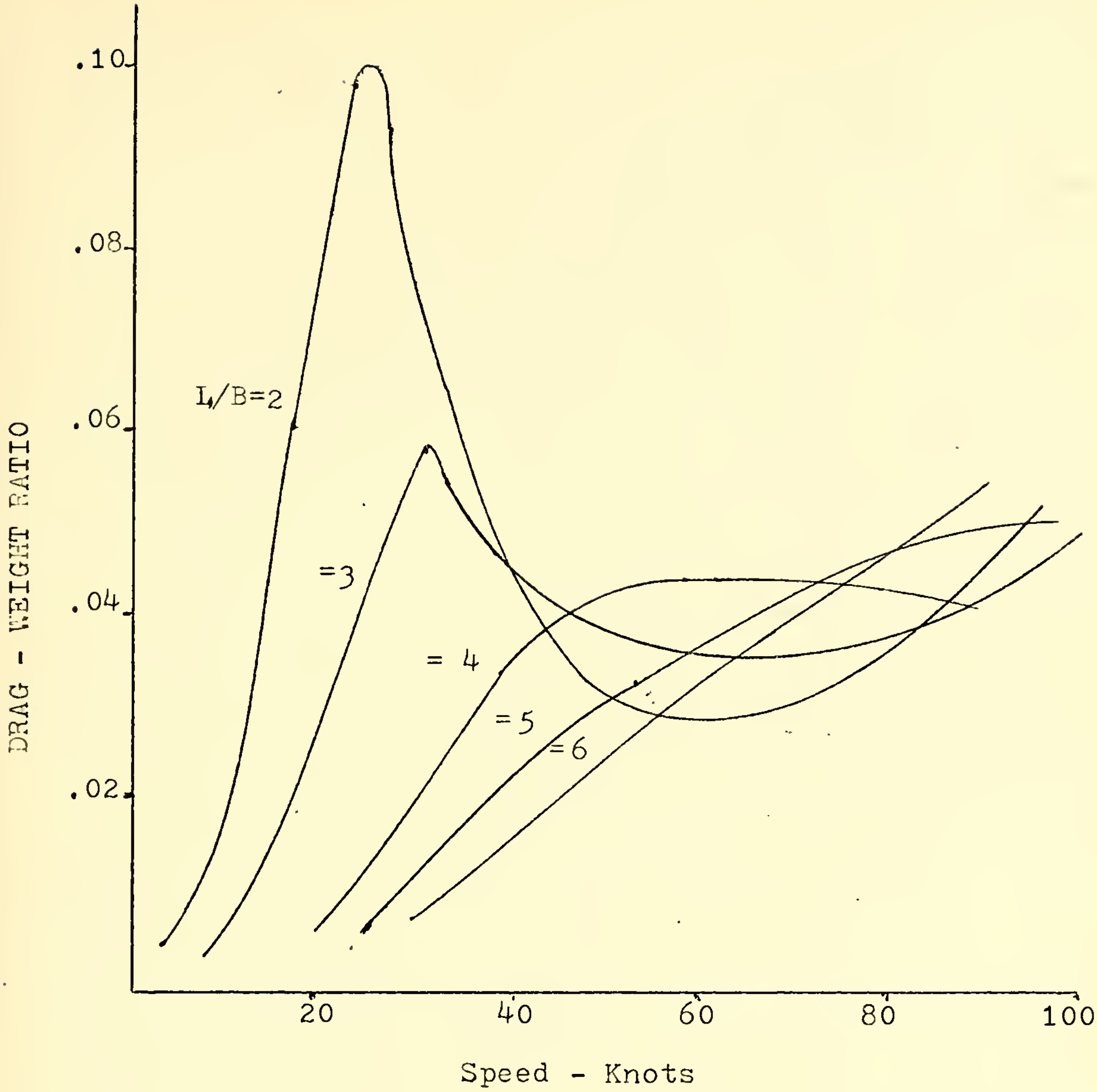


Figure 2 - VARIATION OF DRAG WITH VESSEL SPEED AND LIFT TO DRAG RATIO FOR SURFACE EFFECT SHIPS

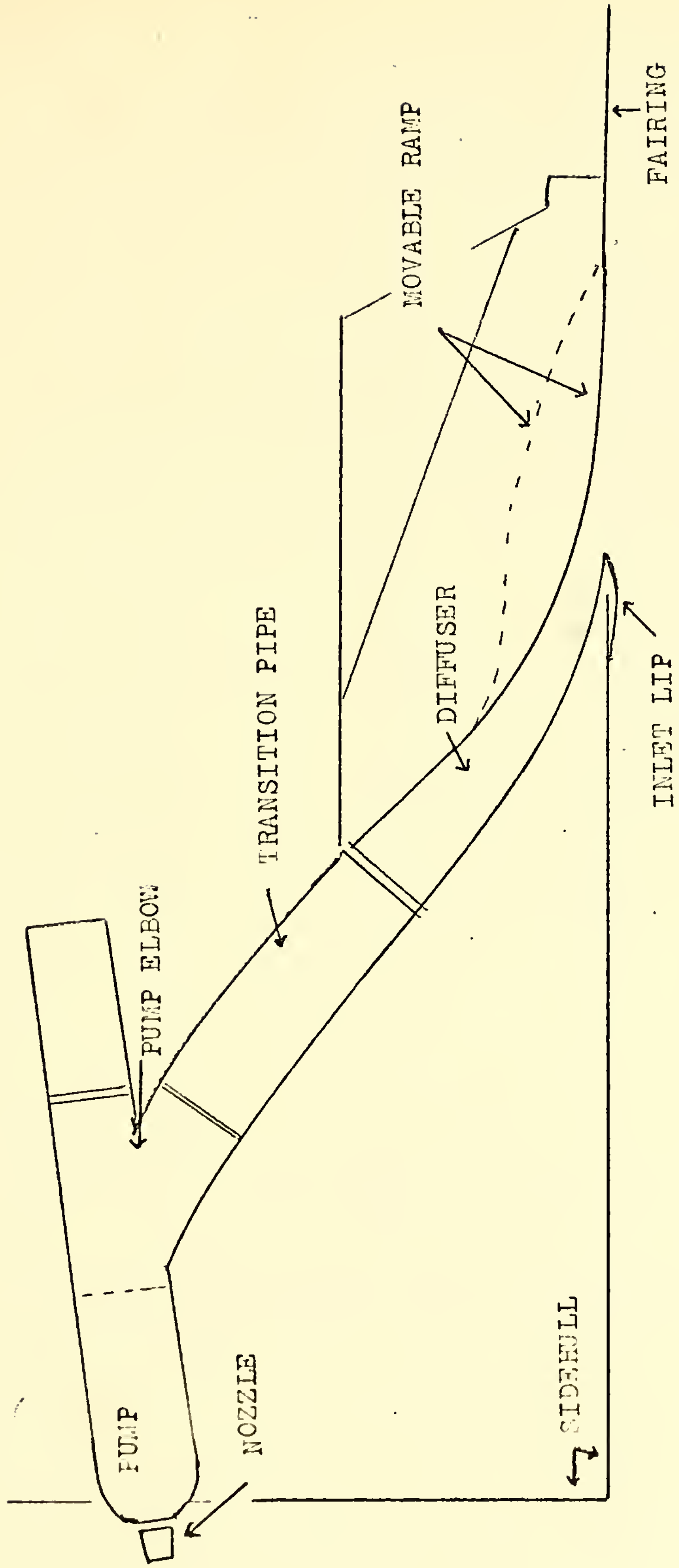


Figure 3 - PROPULSION SYSTEM ARRANGEMENT

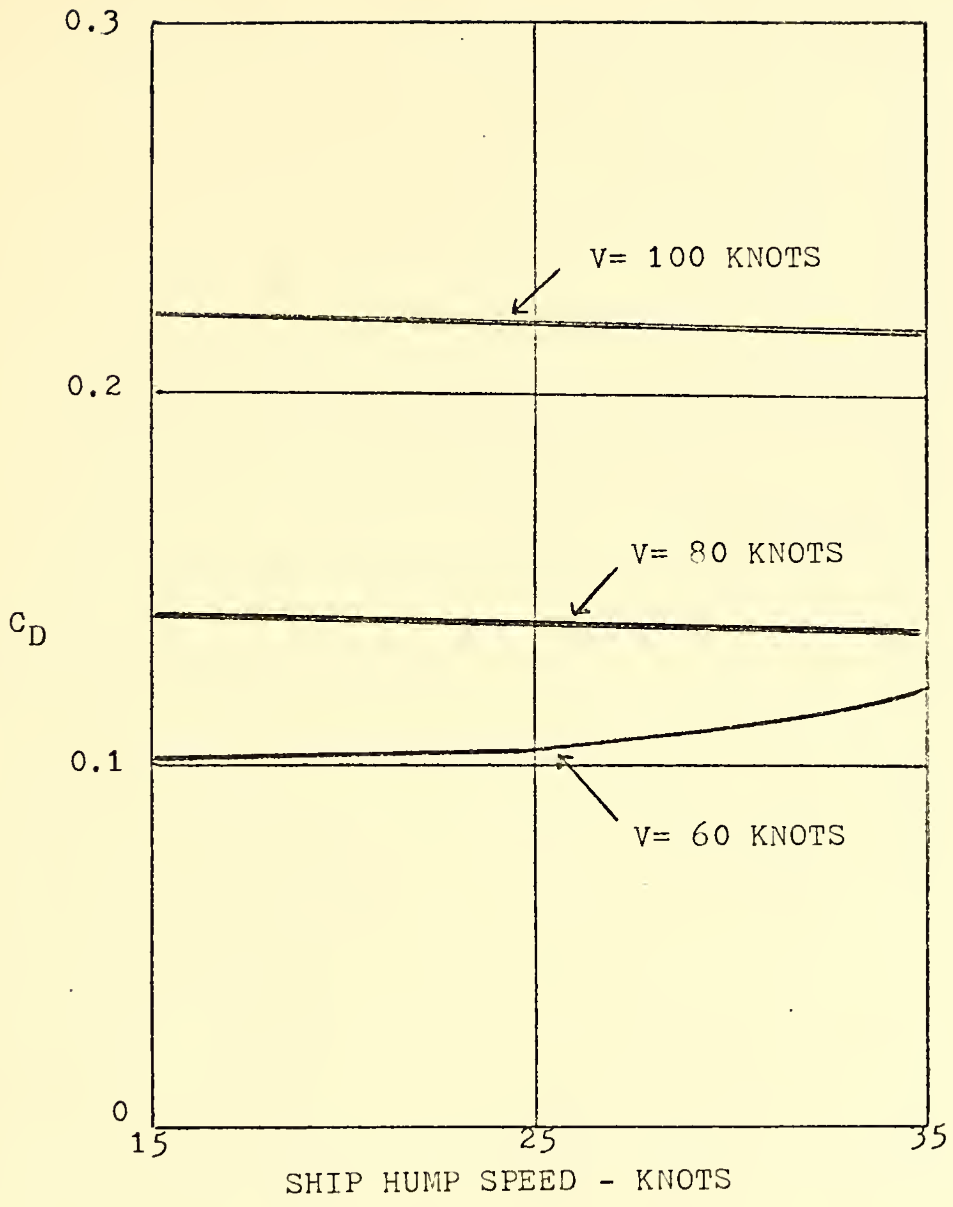


Figure 4 - INLET DRAG COEFFICIENT FOR VARYING APECT RATIO INLETS. (ref. 1)

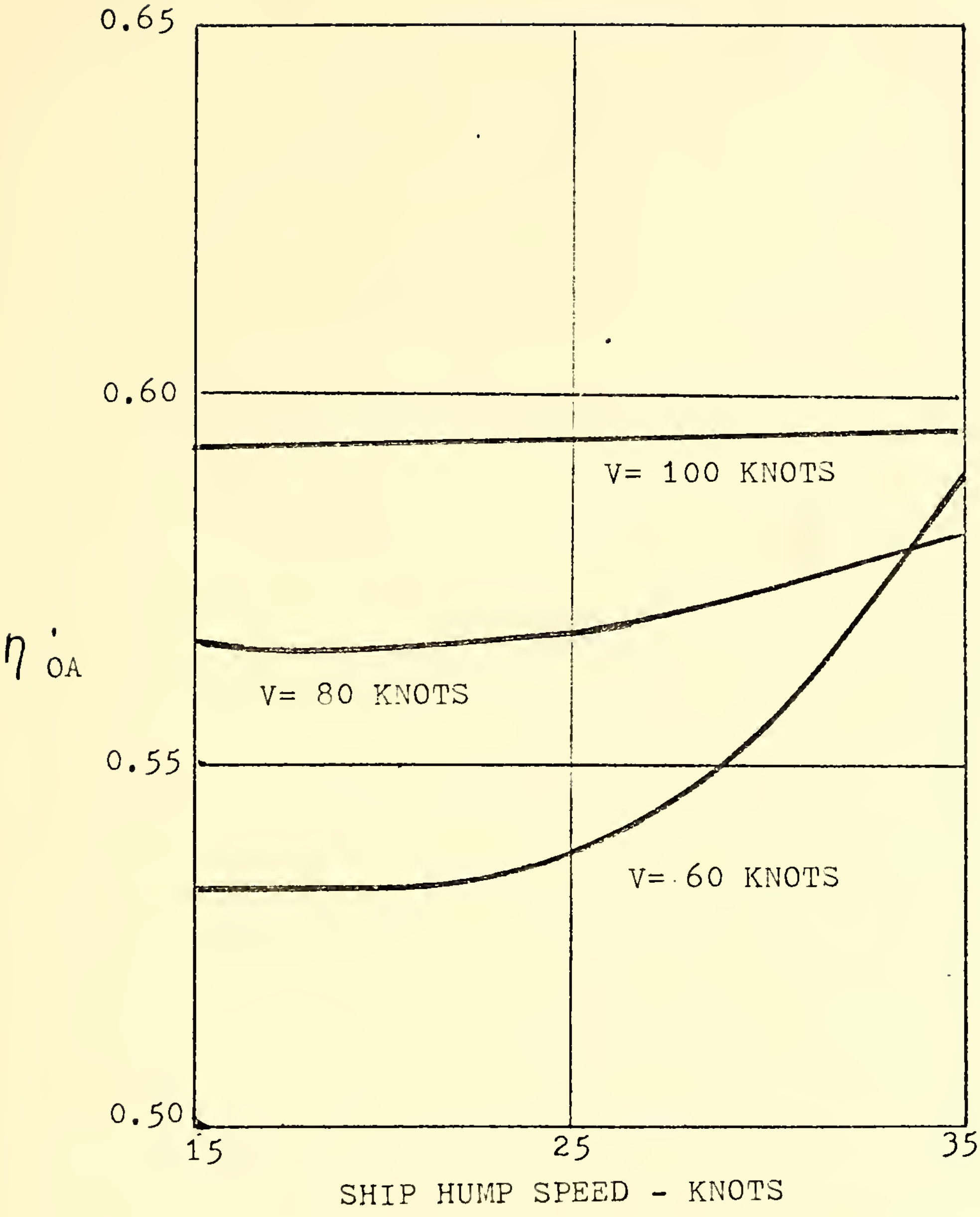


Figure 5 - DESIGN SPEED OVERALL INTERNAL EFFICIENCY FOR VARYING ASPECT RATIO INLETS

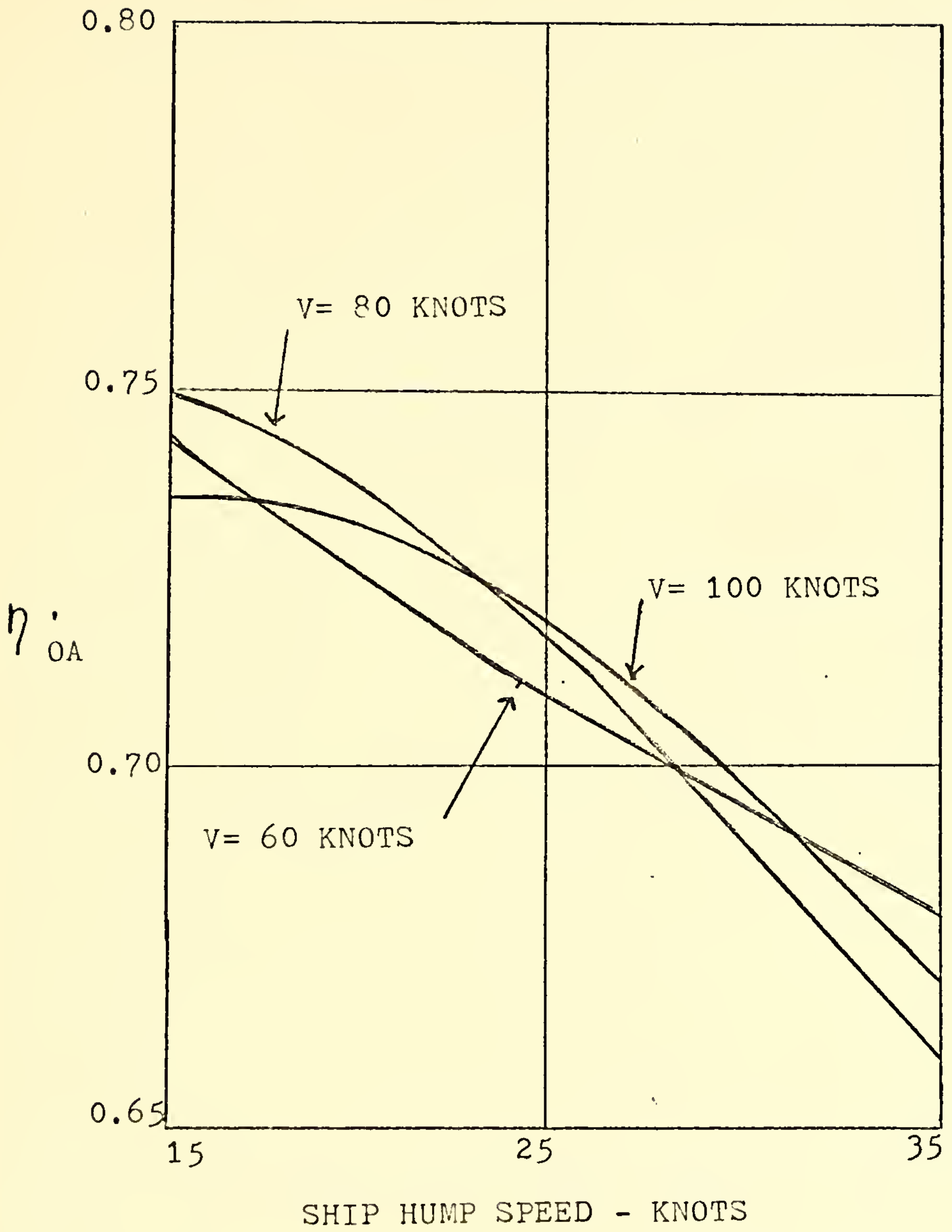


Figure 6 - HUMP SPEED OVERALL INTERNAL EFFICIENCY VARYING ASPECT RATIO INLETS

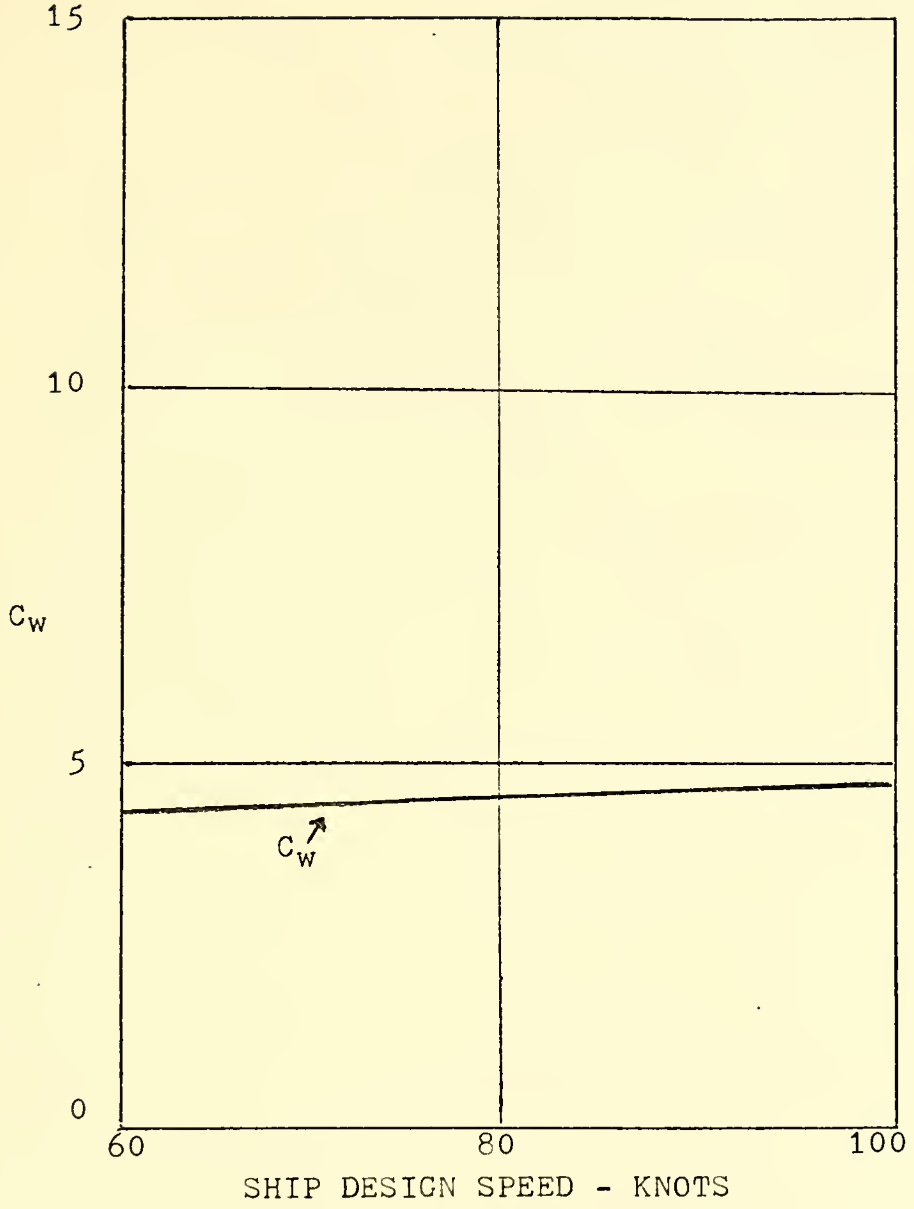


Figure 7 - TOTAL INLET SYSTEM WEIGHT COEFFICIENT FOR VARYING ASPECT RATIO INLETS

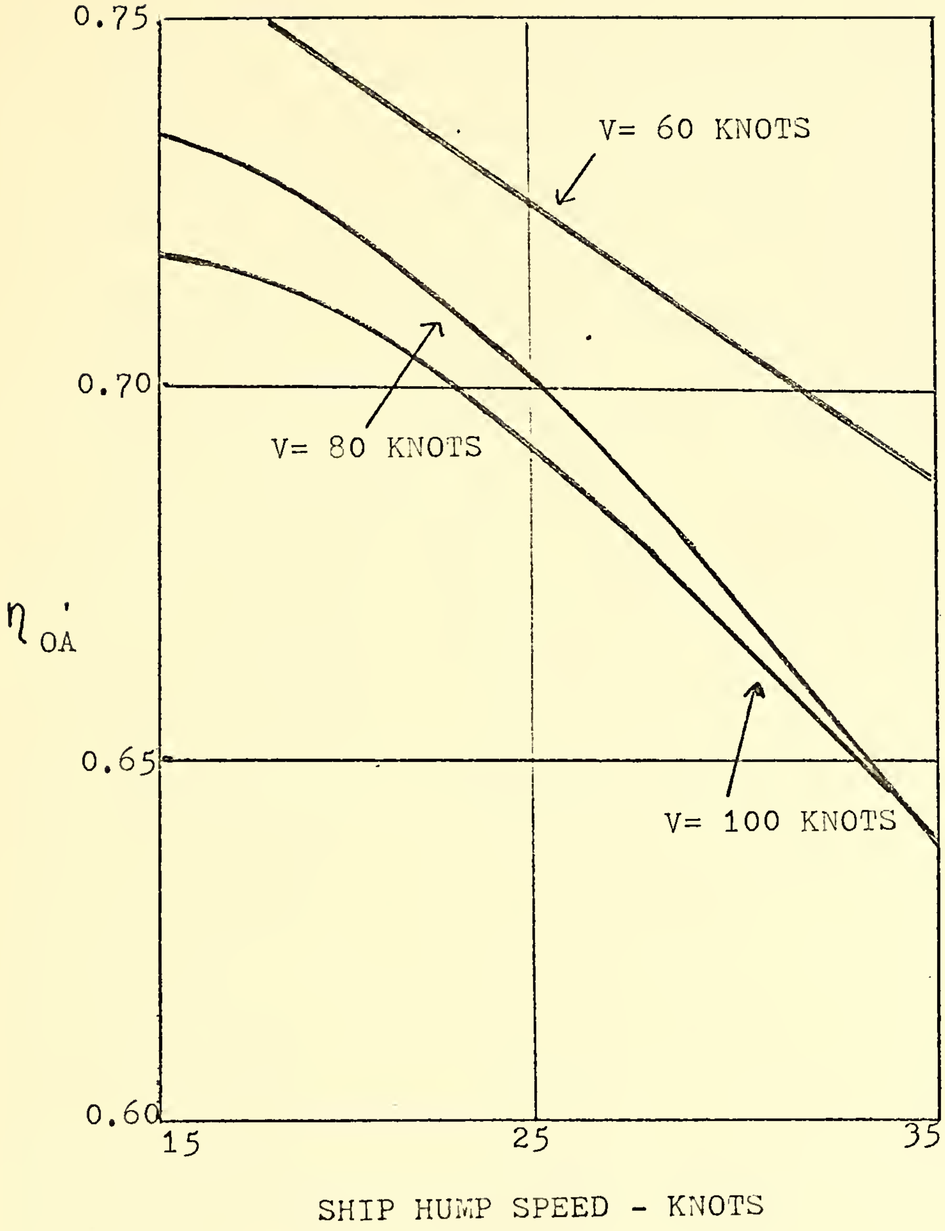


Figure 8 - HUMP SPEED OVERALL INTERNAL EFFICIENCY FOR 2.5 ASPECT RATIO INLETS

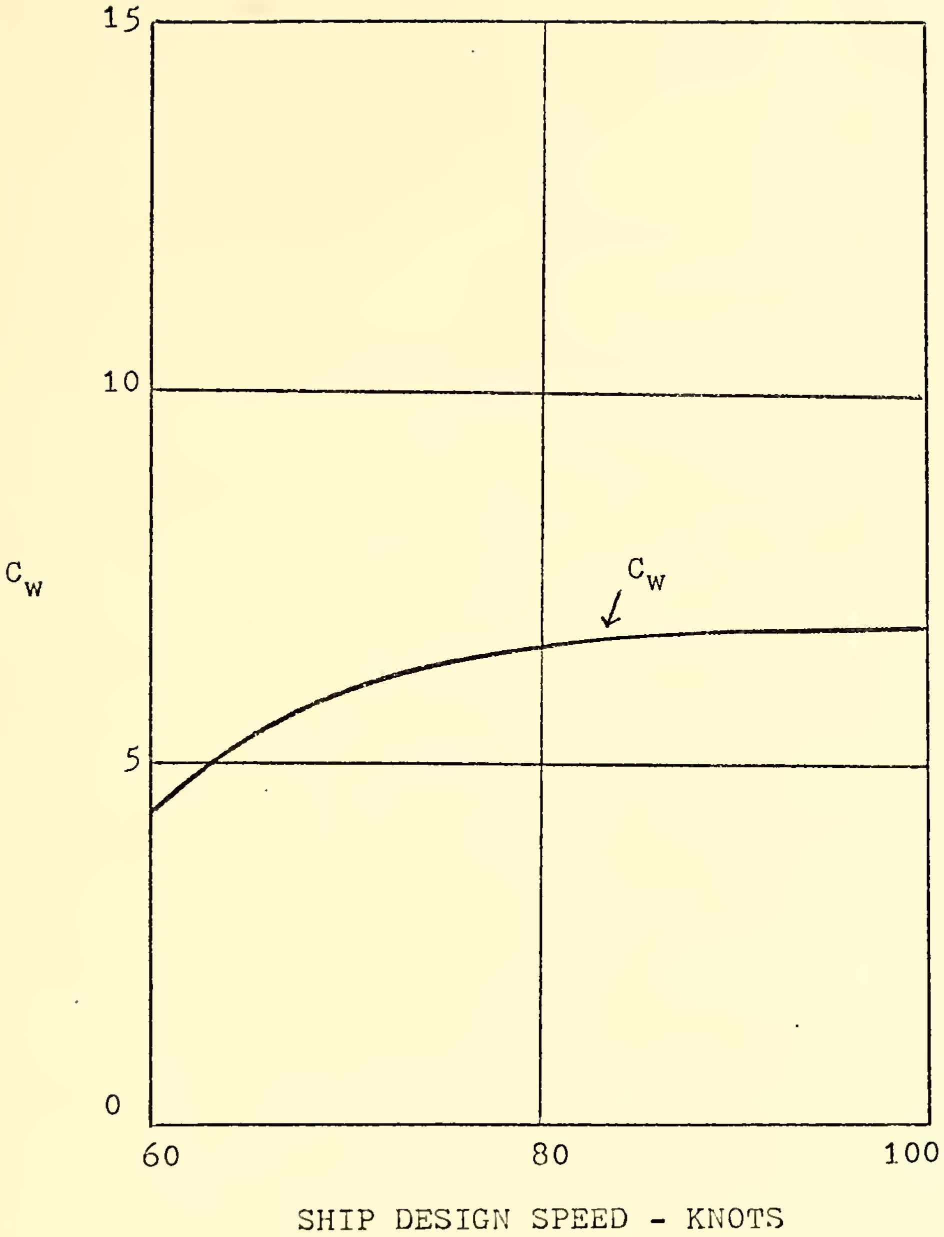


Figure 9 - TOTAL INLET SYSTEM WEIGHT COEFFICIENT FOR 2.5 ASPECT RATIO INLETS

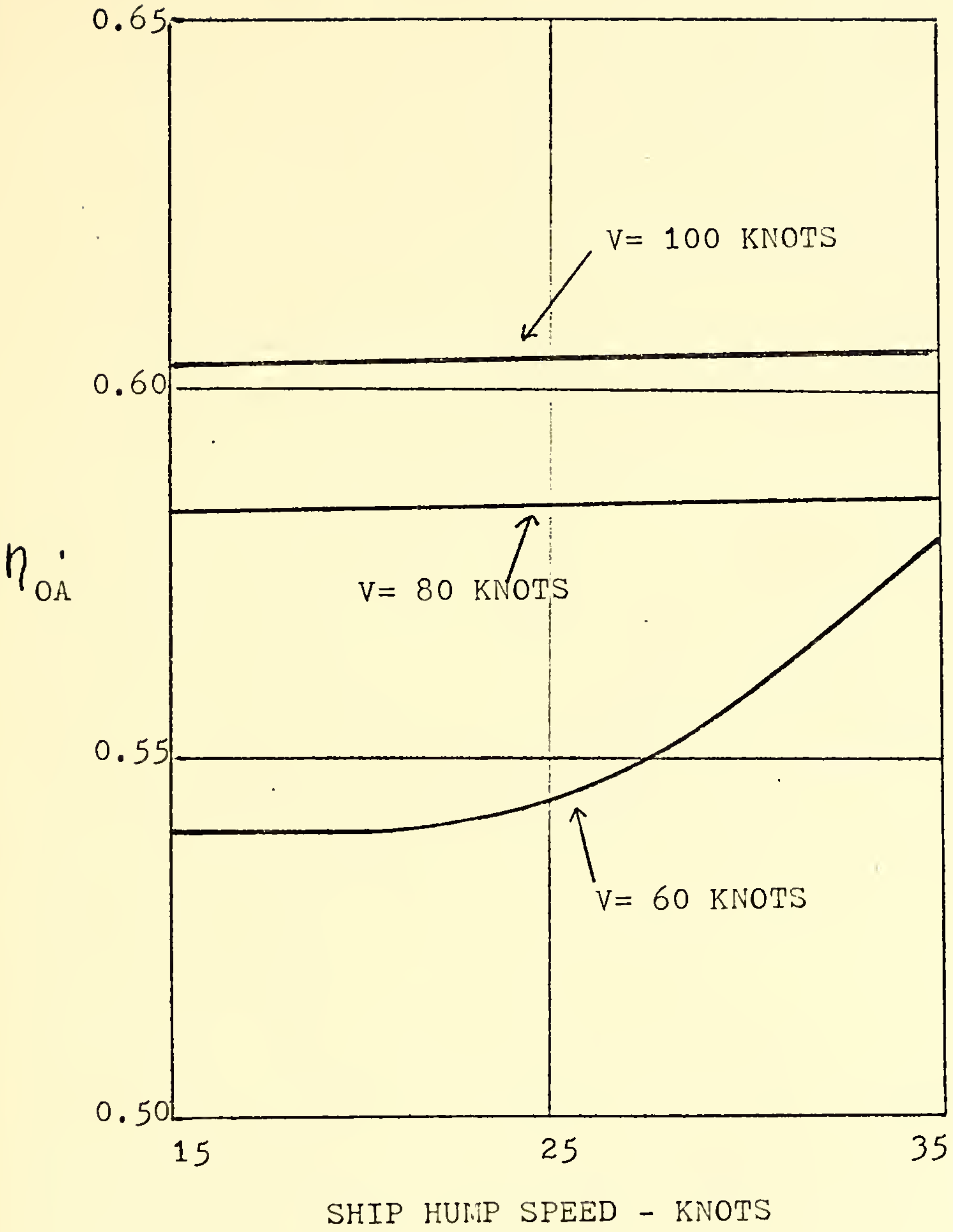


Figure 10 - DESIGN SPEED OVERALL INTERNAL EFFICIENCY FOR 2.5 ASPECT RATIO INLETS

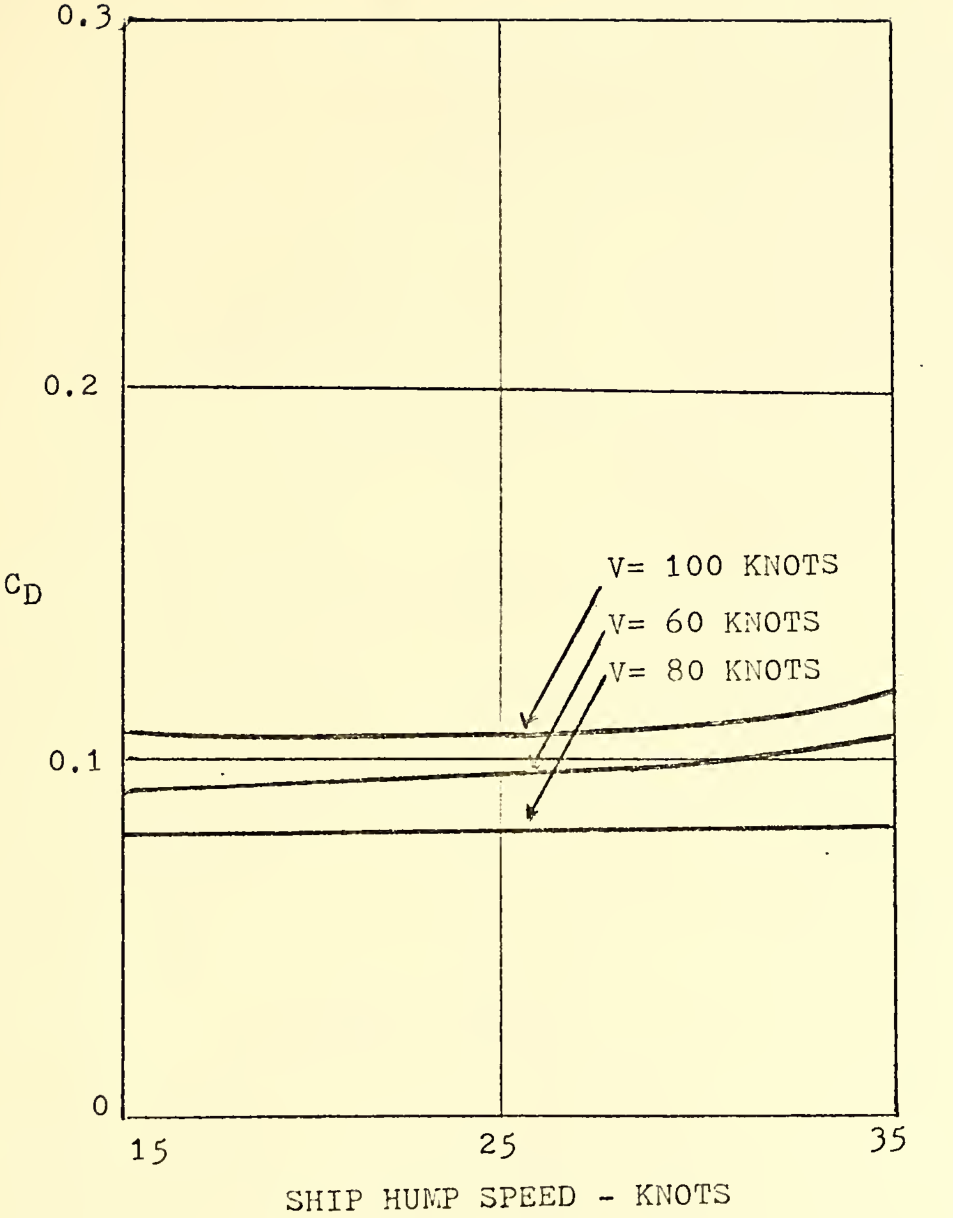
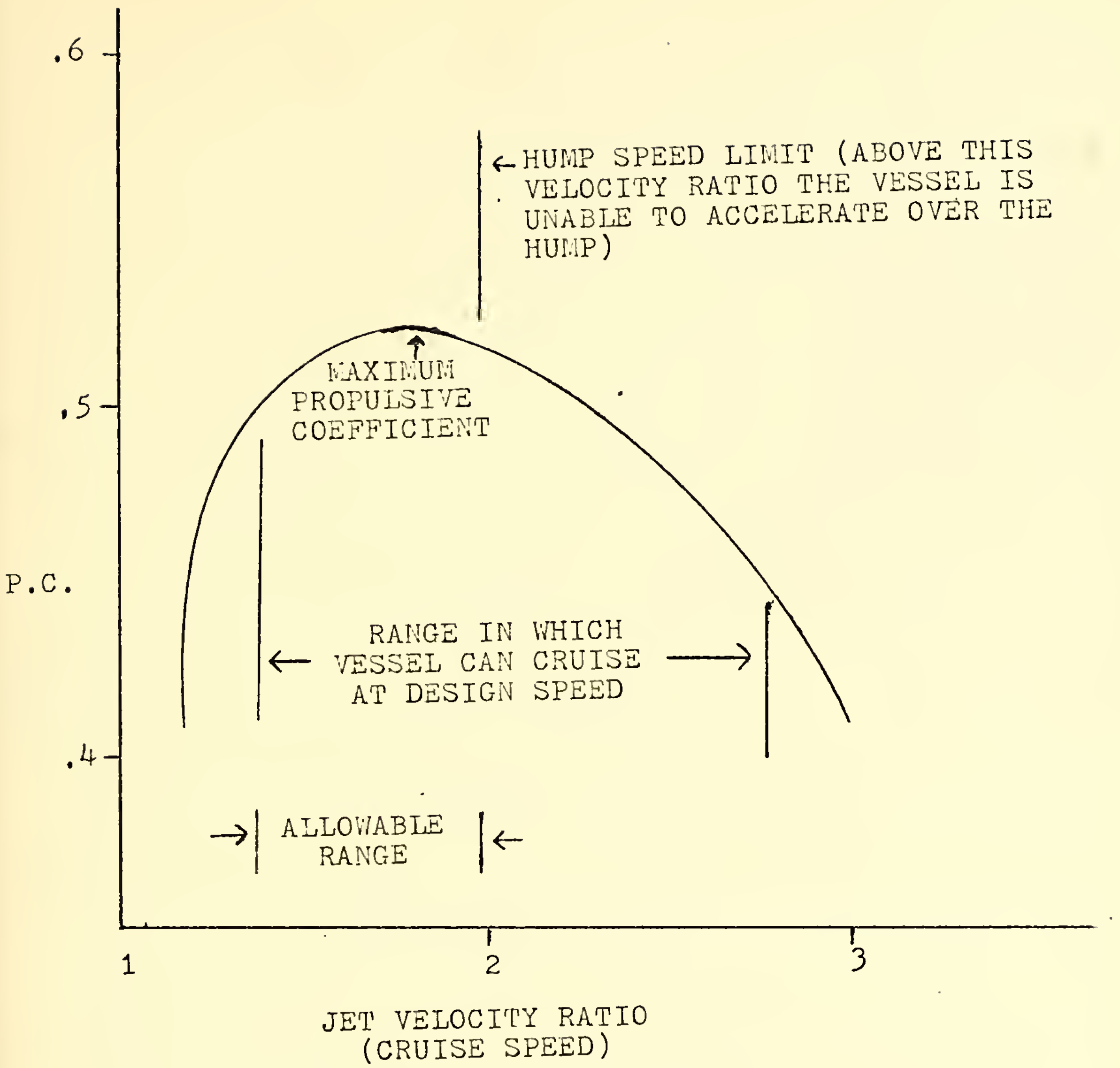


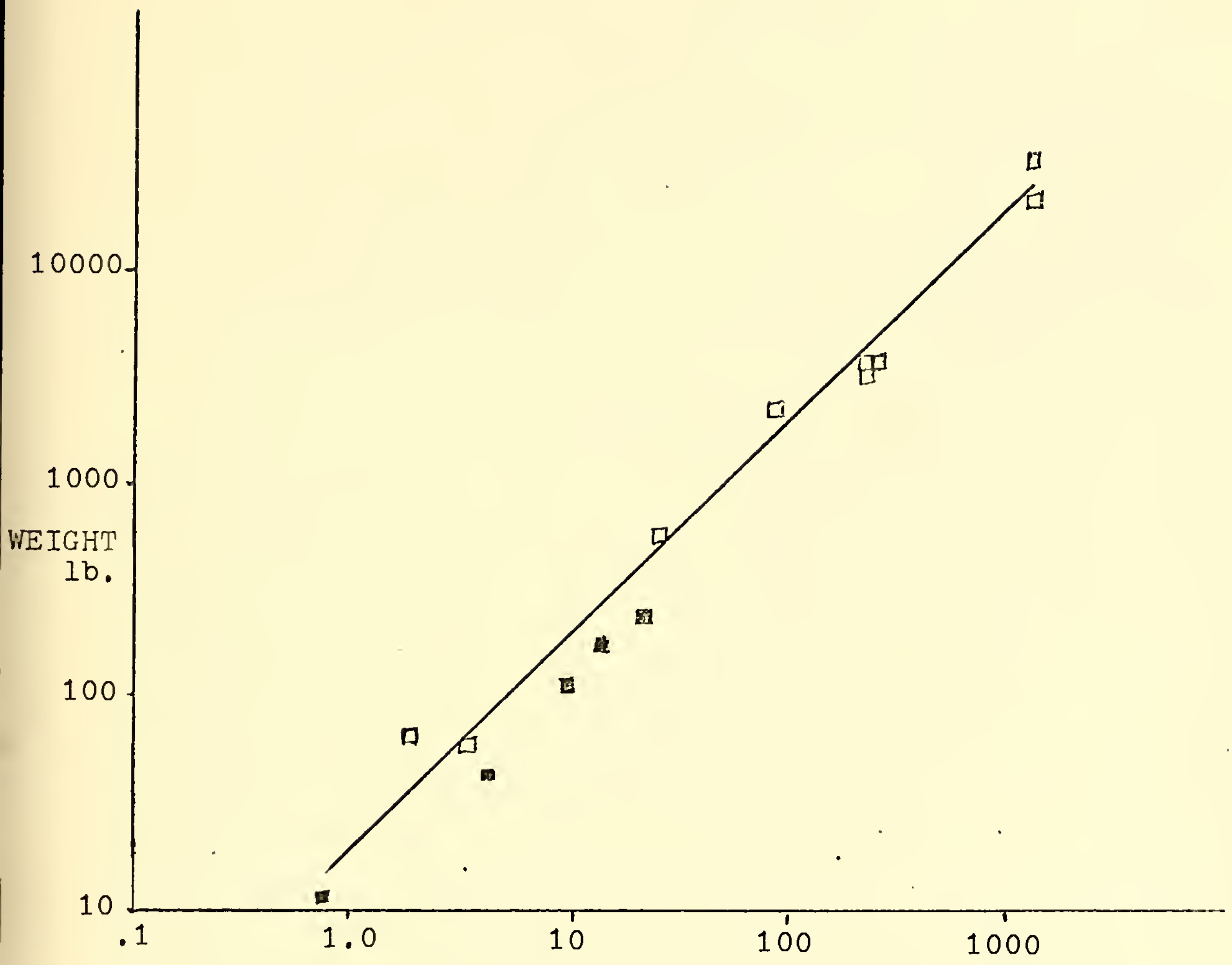
Figure 11 - INLET DRAG COEFFICIENT FOR 2.5 ASPECT RATIO INLETS



Drag = 230,000 lb. at 80 knots
Drag = 325,000 lb. at 30 knots
η_{OA1} = .557 C = .984
η_{OA2} = .577 η_p = .915
C_D = .14 η_g = .98
C_A = 1.2 η_n = .98

Engine normal horsepower = 22,200
Engine maximum horsepower = 22,500
Six engines

Figure 12 - VARIATIONS OF PROPULSIVE COEFFICIENT WITH JET VELOCITY RATIO



Open symbol: simple planetary gears
Closed symbol: compound gears
(Reference 8)

Figure 13 - CORRELATION OF DUDLEY'S METHOD OF ESTIMATING REDUCTION GEAR WEIGHT

TABLE 1

COMPUTER PROGRAM OUTPUT

JET VELOCITY RATIO = 1.946

```
                          WEIGHTS

PUMPS DRY      =  29310.      ENGINES             =  63000.

PUMP WATER     =   6740.      FUEL                = 597913.

INLET SYSTEM   = 139254.      REDUCTION GEARS     =  14262.

TOTAL WEIGHT   = 850481.      ADDITIONAL WATER    =      0.

                          PUMP DATA

NUMBER OF STAGES            =     3   PUMP RPM-CRUISE          =1177.

PUMP EFFICIENCY-CRUISE      = 91.14   PUMP EFFICIENCY-HUMP     =91.13

S. SPEC. SPEED-CRUISE       = 6260.   N.P.S.H. - CRUISE        =186.0

PUMP HEAD - CRUISE          = 921.7   PUMP HEAD - HUMP         =1036.

PUMP INLET DIAMETER         = 2.849   PUMP LENGTH              =5.784

FLOW COEFFICIENT-CRUISE     = .1565   FLOW COEFFICIENT-HUMP    =.1500

TIP VELOCITY-CRUISE         = 175.7   TIP VELOCITY-HUMP        =182.0

PUMP FLOW-CRUISE            = 159.5   PUMP FLOW -HUMP          =158.4


INLET DRAG - CRUISE     = 17764.      TOTAL RESIST.-CRUISE   = 247764

INLET AREA - CRUISE     = 4.332       INLET AREA-HUMP        = 11.51

INLET HEIGHT - CRUISE= 1.038          INLET HEIGHT-HUMP      = 2.760

INLET WIDTH             = 4.171       INLET DIFFUSION RATIO  = 4.016

VARIABLE AREA FACTOR = 2.657          REDUCTION GEAR RATIO   = 2.787
```

TABLE 2

COMPUTER OUTPUT FOR VARIOUS JET VELOCITY RATIOS

VELOCITY RATIO	WEIGHT RATIO	PROPULSIVE COEFFICIENT (OVERALL)	HORSEPOWER HUMP	HORSEPOWER CRUISE	PUMP RPM HUMP
1.6063	0.2306	0.4719	17586.8	20150.7	1007.7
1.6263	0.2260	0.4751	17837.6	20009.3	1021.8
1.6463	0.2219	0.4778	18088.3	19889.3	1035.7
1.6663	0.2182	0.4801	18338.8	19788.3	1049.3
1.6863	0.2147	0.4820	18589.1	19704.0	1062.7
1.7063	0.2116	0.4836	18839.3	19634.8	1075.8
1.7263	0.2087	0.4849	19089.3	19578.9	1088.8
1.7463	0.2072	0.4859	19339.2	19535.2	1101.5
1.7663	0.2048	0.4866	19588.9	19502.4	1114.1
1.7863	0.2025	0.4870	19838.3	19479.5	1126.4
1.8063	0.2005	0.4873	20087.6	19465.6	1138.7
1.8263	0.1985	0.4873	20336.7	19459.8	1150.7
1.8463	0.1968	0.4872	20585.7	19461.6	1162.6
1.8663	0.1952	0.4869	20834.5	19470.2	1174.3
1.8863	0.1937	0.4865	21083.1	19485.0	1185.9
1.9063	0.1923	0.4859	21331.6	19505.7	1197.4
1.9263	0.1910	0.4852	21579.9	19531.7	1208.7
1.9463	0.1898	0.4843	21828.1	19562.6	1219.9

APPENDIX A

ADDITIONAL INLET SYSTEM INFORMATION

Reference 1 is a report on calculated performance of flush inlet systems. It is a study of how various system parameters affect the inlet system's performance. The parameters studied include: the ship's hump speed and design speed, flow rate through the system, variable area factor, lip leading edge radius, aspect ratio, diffusion ratio, diffusion schedule, sidehull geometry, and the ratio of inlet width to fairing width.

The results of the study show that the most important factors affecting the inlet drag are the lip leading edge radius and the variable area factor. The leading edge must be sized to prevent cavitation and the onset of cavitation is determined by the velocity of the entering water. Since this velocity is in part controlled by the area of the inlet, the variable area factor and the lip leading edge radius are coupled. The inlet aspect ratio also affects the inlet drag, with smaller aspect ratio inlets having lower drag coefficients.

The internal efficiency is greatly affected by the diffuser schedule. The schedule used here is as follows:

First 20 percent of length	Diffusion = 6°
20 to 95 percent of length	Diffusion = $6^{\circ} + 12^{\circ}x(p-20)/75$
95 to 100 percent of length	Diffusion = $18^{\circ}x(100-p)/5$

Where p is the pecent of total diffuser length measured from the inlet opening. The use of a smaller diffuser angle will result in higher efficiency but longer and heavier systems. The internal efficiency at hump speed increases with increasing hump speed.

The study covers cruise speeds between 60 and 100 knots and hump speeds between 15 and 35 knots. In general, the vessel's speed has very little influence on the system's drag and efficiency coefficients. The results of the study indicate that the performance coefficients of the system are only slightly affected by jet velocity ratio or by power levels. The power levels considered are between 1,000 and 40,000 horsepower.

It should be noted that the results are based on a minimum amount of data and apply to specific designs. They should be used only for designs similar to the one assumed here. Future data may widen the range of application.

APPENDIX: B SAMPLE CALCULATION

The following sample calculation of the computer program is based on a ship having the following characteristics:

Resistance = 230,000 pounds at 80 knots
= 325,000 pounds at 30 knots
Displacement = 2000 ton Range = 1000 miles
Diffuser outlet height = pump height = 6.5 feet.
Height of waterline = 2.0 feet.
Inlet aspect ratio is variable.
Six LM 2500 gas turbine engines are used.
The acceleration coefficient at hump is 1.2.

From Subroutine SESIN
CDIN1 = .1399
ETA1 = .57535
ETA2 = .69
CWIN = 4.9
C = .984

VO(1) = (80) (1.689) = 135. ft/sec
VO(2) = = 50.7 ft/sec
COR1 = (4.5)(2)(32.2)/(135)(135)(.984)(.984) = .0164
COR2 = = .1128
ETAOA(1) = .5735 - .0164 = .5571
ETAOA(2) = = .577

The portion of the program which compares the number of engines required uses the velocity ratio for maximum propulsive coefficient.

FACT = .984 + .1399/2 - .1399/(2) (135) = 1.053

VJVO (1) = $1.053 + \sqrt{(1.053)(1.053) - (.984)(.984)(.557)}$

VJVO(1) = 1.806. Which is the velocity ratio for maximum PRC. Using an assumed pump efficiency of .9, PRC is:

$$PRC = \frac{(1.73)(1.806 - .984 - .1399/2 + .1399/(2)(135))}{(1.806)(1.806) - (.984)(.5571)}$$

$$= .487$$

The power required must be less than or equal to the available power. The required power is:

$$(230,000)(135) + (.1399)(230,000)/(2(1.806 - .984 - .1399/2))$$

$$= 3.112\text{x}10^7 \text{ ft-lb/sec.}$$

The avalable power is:

$$(22,200)(.487)(550)(6) = 3.56\text{x}10^7 \text{ ft-lb/sec.}$$

Therefore, six engines are sufficient to power the vessel at cruise speed. Having determined this, the program would subtract a designated amount from VJVO(1) and call subroutine PUMP. Since the least weight system in this example occurs at VJVO(1) = 1.946, this velocity ratio will be used for the sample calculation of subroutine PUMP.

$$Q(1) = 230,000/(1.99)(135)(1.946 - .984 - .1399/2)$$

$$= 958 \text{ ft}^3\text{/sec.}$$

$$AJET = 958/(1.946)(135) = 3.655 \text{ ft}^2$$

$$FACT = .5 + 1.2(.1399)/4 = .54199$$

$$VJVO(2) = .54199 + \sqrt{(.54199)^2 + \frac{1.2(320,000)}{1.99(3.655)(50.7)^2}}$$

$$= 5.14$$

$$Q(2) = (3.655)(5.14)(50.7) = 950 \text{ ft}^3\text{/sec.}$$

$$QQ(1) = 958/6 = 159.5 \text{ ft}^3\text{/sec/pump}$$

$$QQ(2) = \quad = 158.4 \text{ ft}^3\text{/sec/pump}$$

$\mathrm{HPP}(1) = ((1.946)(1.946) - (.984)^2(.5571))(135)^2/64.4$

$= 921$ ft.

$\mathrm{HPP}(2) = ((5.14)(5.14) - .577)(50.7)^2/64.4$

$= 1.31$ ft.

$\mathrm{HSV}(1) = 33. + (.984)^2(.5571)(135)^2/64.4 = 186$ ft.

$\mathrm{HSV}(2) = 33. + (.577)(50.7)^2/64.4 = 56.1$ ft.

$\mathrm{QX} = 159.5/158.4 = 1.007$

$\mathrm{HX} = 921/1031 = 0.8933$

Using VTIP = 182 ft/sec.

$\mathrm{RTIP} = 158.4/(3.1416)(182)(.15)(1. - .09) = 1.42$ ft.

$\mathrm{RPM}(2) = 182(60)/(1.42)(2)(3.1416) = 1220$ rpm

$\mathrm{SSS} = (1220)(158.4)^{.5}/ (56.1)^{.75} = 749$

* note: This suction specific speed is 15,900 in the usual dimensions of $\mathrm{rpm(gal/min)}^{.5}/\mathrm{ft}^{.75}$ and below the 16,000 limit.

$\mathrm{SHI} = (32.2)(1031)/(182)^2 = 1.002$. Therefore,

$\mathrm{NSTG} = 3$

$\mathrm{CA} = 1.0(.5)/1.0 = .5$

$\mathrm{CB} = -1.0$

$\mathrm{RX} = -.5(1.007) + \sqrt{(1.007)^2((.5)^2 + 1.0) + .8933}$

$= .9664$

$\mathrm{ETAP}(2) = 1.0 -((3.666/(2)(1.42))^{.165}(1.0 - .915))$

$= .9113$

$\mathrm{PRC}(2) = 2.0(.98)^2(.9113)(5.14 - 1. - .1399(1.2)/2$

$+ .1399(1.2)/(2)(50.7))/((5.14)^2 - .577)$

$= .2748$

The required power at hump speed is:

$$(325,000)(50.7)(1.2) + \frac{(1.2)(.1399)(325,000)}{2(5.14 - 1. -1.2(.1399)/2)}$$

$$= 1.97\text{x}10^7 \text{ ft-lb/sec.}$$

The available power is:

$$(550)(.2748)(22,500)(6) = 2.04\text{x}10^7 \text{ ft-lb/sec.}$$

Therefore, there is sufficient power to accelerate over the hump.

$$\text{ETAX} = -1.7(1.007)^2 + 3.42(1.007) - .72 = 1.0004$$

$$\text{ETAP(1)} = .9113)(1.0004) = .9114$$

$$\text{PRC(1)} = \frac{2(.98)^2(.9114)(1.946 -.98 - .1399/2 +.1399/2(135)}{(1.946)(1.946) - .5571(.984)(.984)}$$

$$= .481$$

The power required at cruise speed is:

$$230,000(135) + .1399(230,000)/2(1.946 -.984 -.1399/2)$$

$$= 3.106\text{x}10^7 \text{ ft-lb/sec.}$$

and the avalable power is:

$$(550)(.481)(22,200)(6) = 3.524\text{x}10^7 \text{ ft-lb/sec.}$$

and the vessel has sufficient power to cruise at the design speed of 80 knots.

RPM(1) = (1220)(.96648) = 1179 rpm.

VTIP(1) = 1179(2)(3.1416)(1.42)/60 = 175.3 ft/sec.

Call subroutine WEIGHT. (NSTG = 3)

XLP = 2.03

CW = 439.5

D1S = 2.84 ft.

The pump dry weight is:

$$\text{XWD} = (439.5)(2.84)^{2.3}(6) = 29,089 \text{ lb.}$$

$PLP = (2.84)(2.03) = 5.76$ ft.

$APUP = (.785)(2.84)^2(.91) = 5.76$ ft^2

The weight of the water in the pump is:

$XWW = (0.523)(5.76)^2(1.99)(32.2)(6) = 6{,}671$ lb.

The weight of the inlet system is:

$XWIN = (4.9)(958)^{1.5} = 139{,}000.$ lb.

$XWENG = 63{,}000.$ lb.

$GERAT = 3400/1220 = 2.78$

$$SHP(1) = \frac{(1.99)(32.2)(958)(921.)}{550(6)(.9114)(.98)(.98)} = 19{,}573 \text{ hp/pump}$$

$$SHP(2) = \frac{(1.99)(32.2)(950)(1031)}{(550)(6)(.9113)(.98)(.98)} = 21{,}730 \text{ hp/pump}$$

The reduction gear q-factor is:

$$RQ = \frac{21{,}730\ (3.78)^3}{3400\ (2.78)} = 124.16$$

and the resulting reduction gear weight is:

$XWGR = (9500)(124.16)(6)/(500) = 14{,}155$ lb.

$SSS1 = (1179)(159.5)^{.5}/(186)^{.75} = 295.6$

or, in standard units, $SSS1 = 6{,}267.$

$CAL = 230{,}000/(2000)(2240) = .051$

$VOTERM = 135. + 135(.1399)/2 = 144.5$

$ETERM = .554(135)^2/\ 64.4 = 157.$

$SCONT = 1.99(32.2)(3.655)/550(.9114)(.98)^2 = .487$

$TI = 1000(1.689)/135(20) = .625$ hr.

$$VJ = 144.5/2 + \sqrt{(144.5)^2/4 + .051(2240)(2000)/1.99(3.655)}$$

$= 262$ ft/sec.

$$\mathrm{SHNG} = .487(262)((262)^2/64.4 - 137)/6 = 19{,}500 \text{ hp.}$$

$$\mathrm{SFC} = .41/(19{,}500/22{,}200)^{.25}\ .423 \text{ lb/hp-hr}$$

$$\mathrm{WT}(1) = .423(19{,}500)(.625)(6) = 31{,}050 \text{ lb.}$$

Which is the weight of fuel for the first time interval. The weight of fuel for the entire mission is:

$$\mathrm{XWF} = 598{,}000 \text{ lb.}$$

$$\mathrm{WTRAT} = \frac{(29089 + 6671 + 139000 + 63000 + 598000)}{2240(2000)}$$

$$= .189$$

$$\mathrm{WTOT} = .189(2000)(2240) = 850{,}000. \text{ lb.}$$

Return to subroutine PUMP.

$$\mathrm{PHI1} = 159.5(182)(.15)/175.3(158.4) = .156$$

$$\mathrm{XDRAG} = .1399(1.99)(958)(135)/2 = 18{,}000 \text{ lb.}$$

$$\mathrm{RESIST} = 230{,}000 + 18{,}000 = 248{,}000 \text{ lb.}$$

Return to main program.

$$\mathrm{AINLET} = 958/135(.8)(2) = 4.33 \text{ ft}^2$$

$$\mathrm{AD} = 5.76(6)/2 = 17.3 \text{ ft}^2$$

$$\mathrm{DR} = 17.3/4.33 = 4.0$$

$$\mathrm{VAF} = 950/50.7(.8)(4.33)(2) = 2.7$$

$$\mathrm{AR} = \mathrm{DR} = 4.0$$

$$\mathrm{HIN} = \sqrt{4.33/4} = 1.04 \text{ ft}$$

$$\mathrm{AIN2} = 2.7(4.33) = 11.7 \text{ ft}^2$$

$$\mathrm{HIN2} = 2.7(1.04) = 2.8 \text{ ft}$$

APPENDIX C

COMPUTER PROGRAM DESCRIPTION AND USER'S GUIDE

The computer program consists of the main program and three subroutines. After reading in the data on the ship, engines, and inlet system as described below, the main program calls subroutine SESIN. This subroutine computes the inlet system's internal efficiencies at hump and cruise speeds and the inlet drag coefficient for the inlet specified. It returns these and "CU" which is the ratio of the entering water's momentum velocity to the vessel's speed.

The main program then computes the jet velocity ratio for maximum propulsive coefficient. Using the resulting velocity ratio and an assumed pump efficiency of .90 and nozzle and gear efficiences of .98, the program computes the number of engines required.

Since the jet velocity ratio is the only system variable, the program is quite simple. The velocity ratio is varied in steps and subroutine PUMP is called. Subroutine PUMP returns the systems weight ratio and other data. The velocity ratio is increased until either the number of required pump stages exceeds three or the required power at either hump or cruise speeds exceeds the available power. The calculated data is then printed out and execution terminates.

Subroutine PUMP uses the equations developed in chapters 3 and 4 to find the required flow rates, pump heads, and net positive suction heads at cruise and hump speeds for the given

jet velocity ratio. It then designs the pump using these values and the tip velocity and suction specific speeds constraints. The pump is designed at hump speed to meet the stated criterion. The pump efficiency is determined by the pump diameter and a test is made to determine if sufficient power is available to accelerate over the hump. If there is sufficient power, the cruise speed performance is calculated, the pump is tested, and subroutine WEIGHT is called.

Subroutine WEIGHT uses the equations developed in chapter 4 to calculate the system weight. The exit angle of the diffuser is assumed to be 45 degrees and the transition pipe between the diffuser and the pump is assumed to be straight. The length of the pipe is then 1.414 times the difference in height between the diffuser and pump. The weight of the water in the pipe is calculated using this length. The user may wish to vary this angle and include other weights such as the weight of the pipe itself or a nozzle weight (XWPIP).

The user of the program must supply the following inputs to the program:

1. Engine performance data. The first twelve data cards in the program at present are engine data cards. (See "LIST OF PROGRAM VARIABLES, PERF (N,IENGN)", BELOW.)

2. A data card containing:
   IENGN - The type of engine to be used
   IAR - The type of inlet to be used
   NGT - The number of engines to be used (optional)

3. A data card containing:
   HE - The height of the diffuser exit above
   the inlet in feet

HEP - The height of the pump above the inlet in feet.
HEW - The height of the outside waterline above the inlet in feet.
CAC - The acceleration coefficient.

4. A data card containing:
VO (1) - The ship's cruise speed in knots
VO (2) - The ship's hump speed in knots
DRAG (1) - The hull drag at cruise speed in pounds
DRAG (2) - The hull drag at hump speed in pounds
DISP - The ship's displacement in long tons
RANGE - The range in nautical miles

LIST OF PROGRAM VARIABLES

AD	- Diffuser outlet area	ft^2
AINLET	- Inlet area at cruise speed	ft^2
AIN2	- Inlet area at hump speed	ft^2
AJET	- Jet area	ft^2
APUP	- Pump inlet area	ft^2
AR	- Inlet aspect ratio	
C	- $=(CU)^2$ The square of the ratio of the momentum velocity of entering water to the ship's velocity	
CAC	- Acceleration coefficient	
CAL	- Ratio of ship's drag to displacement	
CDIN1	- Inlet drag coefficient at cruise speed	
CDIN (I)	- Inlet drag coefficient	
COR1	- Correction factor for ETAOA (1)	
COR2	- Correction factor for ETAOA (2)	
CU	- Ratio of momentum velocity of inlet water to ship's velocity	
CW	- Pump weight coefficient	
CWIN	- Inlet system weight coefficient	
D1S	- Pump inlet diameter	
DCOF	- Inlet drag coefficient (subroutine weight)	
DEL	- Increment of change in jet velocity ratio	

DIS(1)	- Displacement after removing fuel	lb
DISP	- Displacement - entered in long tons converted to pounds	
DR	- Diffusion ratio	
DRAG (I)	- Ship's drag	lb
DRAT	- Ratio of pump's inlet hub radius to blade tip radius	
ENETA	- Overall internal efficiency times the square of the ratio of momentum velocity to ship velocity (used in subroutine weight)	
ETA1	- η_{OA}' at cruise speed	
ETA2	- η_{OA}' at hump speed	
ETAOA (I)	- η_{OA}	
ETAP (I)	- Pump efficiency	
ETAX	- Ratio of off design point pump efficiency to design point efficiency	
G	- Acceleration due to gravity	ft/sec^2
GERAT	- Reduction gear ratio	
HA	- Atmospheric pressure head	ft
HE	- Height of diffuser outlet above baseline	ft
HEP	- Height of pump above baseline	ft
HEW	- Height of outside waterline above baseline	ft
HIN	- Inlet height (dimension) at cruise speed	ft

HIN2	- Inlet height (dimension) at hump speed	ft
HPP(I)	- Head across pump	ft
HSV(I)	- Net positive suction head	ft
HX	- Ratio of pump head at cruise to pump head at hump	
IAR	- Input to program = 1 for 2.5 aspect ratio inlets = 2 for varying aspect ratio inlets	
ICONT	- Program control	
IENGN	- Type of gas turbine = 1 - TF 35 = 2 - TF 40 = 3 - Proteus, 1500 RPM = 4 - Proteus, 1000 RPM = 5 - Tyne 1A = 6 - Tyne 1C = 7 - FT12 A = 8 - LM 1500 = 9 - LM 2500 =10 - FT4A-2C =11 - FT4A-12 =12 - FT4C-2	
IPRINT	- Output device number	
IREAD	- Input device number	
ISTEER	- Program control	
LAST	- Program control	
NGT	- Number of gas turbines	
NSTG	- Number of pump stages	
PC(L,M)	- Inducer stage characteristics	
PCA(L,M)	- Axial stages characteristics	
PC1MAX	- Maximum overall propulsive coefficient	
PC2MAX	- Maximum 'false' propulsive coefficient (ship's hull drag times cruise speed/550 SHP)	
PC1VJ	- Jet velocity ratio for PC1MAX	

PC2VJ	- Jet velocity ratio for PC2MAX	
PCOEF (J,K)	- Pump length and weight coefficients	
PERF (N,IENCN)	- Engine data where N is	
	1 - Normal SHP	HP
	2 - Maximum SHP	HP
	3 - SFC At normal SHP	$\frac{lb}{HP - hr}$
	4 - RPM	RPM
	5 - Weight of engine (dry)	lb
PHI	- Pump flow coefficient at hump speed	
PHI1	- Pump flow coefficient at cruise speed	
PI	- Constant = 3.1415927	
PLP	- Pump length	ft
PRC (I)	- Propulsive coefficient (overall)	
PRC1	- Propulsive coefficient (overall) main program	
PRNC1	- Propulsive coefficient (false) main program	
Q (I)	- Flow rate through system	ft^3/sec
QQ (I)	- Flow rate through each pump	ft^3/sec/ pump
QX	- Ratio of flow rate at cruise speed to flow rate at hump speed	
RANGE	- Ships Range	nautical miles
RESIST	- Total resistance of ship including inlet drag	lb
RHOW	- Density of water	$\frac{slug - ft^4}{sec^2}$

RPM (I)	Pump RPM	RPM
RPM2	Pump RPM at hump speed (subroutine SESIN)	RPM
RQ	Reduction gear Q-factor	
RTIP	Pump inlet tip radius	ft
RX	Ratio of pump RPM at cruise speed to RPM at hump speed	
SFC	Specific fuel consumption	$\frac{lb}{HP - hr}$
SHI	Pump head coefficient	
SHNG	Shaft horsepower required after fuel is removed	HP
SHP (I)	Shaft horsepower	HP
SSS1,2	Suction specific speed cruise speed and hump speed	
TI	Time interval for fuel consumption calculation	hr
VAF	Variable area factor (ratio of inlet area at hump speed to inlet area at cruise speed)	
VO(I)	Ship velocity input and subroutine SESIN remainder of program	KTS ft/sec
VJ	Jet velocity	ft/sec
VJVO(I)	Jet velocity ratio	
VTIP(I)	Pump blade tip velocity	ft/sec
WIDTH	Width of inlet opening	ft
WT(K)	Weight of fuel required for one time period	lb
WTMIN	Minimum weight ratio	
WTOT	Total system weight	lb
WTRAT	Weight ratio	

WVJ - Jet velocity ratio for minimum weight ratio lb

XDRAG - Inlet system drag

XKEEP - Minimum weight ratio (subroutine pump)

XK - Reduction gear K - factor

XN - Factor for SFC versus power curve

XNGT - Number of gas turbines

XWD - Pump dry weights lb

XWENG - Weight of engines lb

XWF - Total fuel weight lb

XWGR - Reduction gear weight lb

XWIN - Inlet system weight lb

XWPIP - Transition pipe weight (user may add additional weights) lb

XWW - Pump water weight lb

XX(J,K) - Main program outputs where

- 1 - Jet velocity ratio
- 2 - Weight ratio
- 3 - Overall propulsive coefficient
- 4 - False propulsive coefficient
- 5 - Shaft horsepower at hump speed HP
- 6 - Shaft horsepower at cruise speed HP
- 7 - Suction specific speed at hump speed
- 8 - Pump RPM at hump speed RPM

9 - Number of pump stages

XLP - Pump length coefficient

*Note A. As used above (I) indicates ship's speed.

I = 1 - Cruise speed
= 2 - Hump speed

```
C     SURFACE EFFECT SHIP FLUSH INLET WATERJET SYSTEM
      COMMON/ROUT/PRO1,SSS2,RPM2
      COMMON/INDEX/IAR,IPRINT,IREAD,IENGN,NSTG,LAST
      COMMON/PARIN/ETA1,ETA2,CU,CDIN1
      COMMON OWIN
      COMMON/HEAD/HA,HEW,HEP,Q(2),HE
      COMMON/PERFO/PERF(5,12),WTRAT,XNGT
      COMMON/CONST/PI,G,RHOW,XK
      COMMON/PUMA/CAC,COP1,COR2
      COMMON/SHIP/DISP,RANGE,DRAG(2)
      COMMON/WEMA/APUP,GERAT,SHP(2)
      DIMENSION ETAOA(2),CDIN(2),XX(20,9),PRO(2)
      IREAD=8
      IPRINT=5
      DO 2 J=1,12
      READ(IREAD,1003)(PERF(I,J),I=1,5)
 1003 FORMAT(5F10.3)
    2 CONTINUE
      READ(IREAD,1001) IENGN,IAR,NGT
 1001 FORMAT(3I5)
      READ(IREAD,1002) HE,HEP,HEW,CAC
 1002 FORMAT(4F10.2)
      READ(IREAD,1000) VO(1),VO(2),DRAG(1),DRAG(2),DISP,RANGE
 1000 FORMAT(6F10.1)
      WRITE(IPRINT,5000) DISP,DRAG(1),VO(1),DRAG(2),VO(2)
 5000 FORMAT(1H1,20X,'THIS RUN IS FOR A ',F7.1,' TON SES WHOSE DRAG IS '
     1,F9.1,' POUNDS AT ',F6.1,' KNOTS'/21X,'AND ',F9.1,' POUNDS AT A HU
     2MP SPEED OF ',F5.1,' KNOTS'//)
      DISP=DISP*2240.
      PI=3.1415927
      HA=33.0
      G=32.174
      RHOW=1.99
      XK=500.
      CALL SESIN
C     CONVERT VELOCITIES TO FEET/SECOND
```

```
      DO 3 I=1,2
      VO(I)=VO(I)*1.689
    3 CONTINUE
      COR1=(HE-HEW)*2.*G/(VO( 1)*VO(1)*CU*CU )
      COR2=(HE-HEW)*2.*G/(VO(2)*VO(2))
C     COMPUT NGT REQUIRED  ASSUMING VJVO=1.8 AND THE PRODUCT
C     OF THE NOZZLE,GEAR, AND PUMP EFFICIECIES = .865
      ETAOA(1)=ETA1-COR1
      CDIN(1)=CDIN1
      FACT=CU+CDIN(1)/2.-CDIN(1)/(2.*VO(1))
      VJVO(1)=FACT+SQRT(FACT*FACT-CU*CU *ETAOA(1)+2.*G*(HEP-HE)/(VO(1)*
     1VO(1)))
      PRC(1)=1.73*(VJVO(1)-CU-CDIN(1)/2.+CDIN(1)/(2.*VO(1)))/(VJVO(1)*
     1VJVO(1)-CU*CU *ETAOA(1)+2.*G*(HEP-HE)/(VO(1)*VO(1)))
      IF(NGT.GT.0) GO TO 40
      NGT=2
   40 XNGT=FLOAT(NGT)
      IF(DRAG(1)*VO(1)+CDIN(1)*DRAG(1)/(2.*(VJVO(1)-CU-CDIN(1)/2.)).LE.
     1PERF(1,IENGN)*PRC(1)*XNGT*550.) GO TO 45
      NGT=NGT+2
      GO TO 40
   45 CONTINUE
      WRITE(IPRINT,5001)NGT
 5001 FORMAT(5X,'NUMBER OF ENGINES=',I3///)
      I=0
      IJ=0
      PC2MAX=0.0
      PC1MAX=0.0
      WTMIN=1.0
      DEL=0.02
      VJVO(1)=VJVO(1)-10.*DEL
   50 CONTINUE
      CALL PUMP
      IJ=IJ+1
      IF(IJ.GT.35) GO TO 42
      GO TO 43
```

```
42 IF(I.EQ.0) GO TO 78
43 CONTINUE
   PRNC1=DRAG(1)*VO(1)/(XNGT*SHP(1)*550.)
   IF(WTRAT.GE.1.0) GO TO 57
   IF(WTMIN.LT.WTRAT)GO TO 51
   WTMIN=WTRAT
   WVJ=VJVO(I)
51 CONTINUE
   IF(PC1MAX.GT.PRC1) GO TO 52
   PC1MAX=PRC1
   PC1VJ=VJVO(1)
52 CONTINUE
   IF(PC2MAX.GT.PRNC1) GO TO 53
   PC2MAX=PRNC1
   PC2VJ=VJVO(1)
53 CONTINUE
   GO TO 54
57 CONTINUE
   IF(I.GT.0) GO TO 60
   VJVO(1)=VJVO(1)+DEL
   GO TO 50
54 I=I+1
   IF(I.GT.20) GO TO 60
   XX(I,1)=VJVO(1)
   XX(I,2)=WTRAT
   XX(I,3)=PRC1
   XX(I,4)=PRNC1
   XX(I,5)=SHP(2)
   XX(I,6)=SHP(1)
   XX(I,7)=SSS2*21.2
   XX(I,8)=RPM2
   XX(I,9)=FLOAT(NSTG)
   VJVO(1)=VJVO(1)+DEL
   GO TO 50
60 CONTINUE
   AINLET=Q(1)/(VO(1)*.8*2.)
```

```
      AC=APUP*XNGT/2.
      CR=AC/AINLET
      VAF=Q(2)/(VC(2)*.8*AINLET*2.)
      IF(IAR.EQ.2) GO TO 75
      AR=2.5
   74 CONTINUE
      HIN=SQRT(AINLET/AR)
      WIDTH=AR*HIN
      GO TO 76
   75 AR=CR
      GO TO 74
   76 CONTINUE
      AIN2=VAF*AINLET
      HIN2=VAF*HIN
      WRITE(IPRINT,4100) AINLET,AIN2,HIN,HIN2,WIDTH,CR,VAF,GERAT
 4100 FORMAT(5X,'INLET AREA-CRUISE ***********=',F10.4,10X,'INLET AREA-H
     1UMP ************=',F10.4/5X,'INLET HEIGHT-CRUISE *********=',F10
     2.4,10X,'INLET HEIGHT-HUMP ************=',F10.4/5X,'INLET WIDTH ***
     3**************=',F10.4,10X,'INLET DIFFUSION RATIO ********=',F10.4
     4/5X,'VARIABLE AREA FACTOR ********=',F10.4,10X,'REDUCTION GEAR RAT
     5IO *********=',F10.4///)
      WRITE(IPRINT,4200) PC1MAX,PC1VJ,PC2MAX,PC2VJ,WTMIN,WVJ
 4200 FORMAT(5X,'MAXIMUM OVERALL PROPULSIVE COEFFICIENT=',F10.6,' AT VJV
     1C=',F10.4/6X,'MAXIMUM FALSE  PROPULSIVE COEFFICIENT=',F10.6,' AT V
     2JVC=',F10.4/17X,'MINIMUM TOTAL WEIGHT RATIO=',F10.6,' AT VJVC=',F1
     30.4)
      WRITE(IPRINT,4300)
 4300 FORMAT(1H1,'   VELOCITY   WEIGHT     PROPULSIVE      PROPULSIVE
     1HORSEPOWER    HORSEPOWER     SUCTION       PUMP     NUMBER')
      WRITE(IPRINT,4310)
 4310 FORMAT(4X,'RATIO',6X,'RATIO',4X,'COEFFICIENT',4X,'COEFFICIENT',7X,
     1'HUMP',9X,'CRUISE',6X,'SPECIFIC',5X,'RPM',7X,'OF'/25X,'(OVERALL)',
     26X,'(FALSE )',35X,'SPEED',7X,'HUMP    STAGES'//)
      WRITE(IPRINT,4400)((XX(L,K),K=1,9),L=1,I)
 4400 FORMAT(//  20(4X,F6.4,4X,F6.4,7X,F6.4,8X,F6.4,9X,F7.1,7X,F7.1,5X,
     1F7.1,4X,F6.1,5X,F3.1//))
```

```
      WRITE(IPRINT,4500)
 4500 FORMAT(1H1)
   78 CONTINUE
      STOP
      END
```

```
      SUBROUTINE SESIN
      COMMON/PARIN/ETA1,ETA2,CU,CDIN1
      COMMON/INDEX/IAR,IPRINT,IREAD,IENGN,NSTG,LAST
      COMMON/VELOC/VO(2),VJVO(2)
      COMMON CWIN
C     CALCULATION OF OVERALL INTERNAL EFFICIENCY FOR 2.5 ASPECT
C     RATIO INLETS
      IF (IAR.EQ.2) GO TO 30
      F=.602
      E=.584
      D=0.00015*VO(2)*VO(2)-.0056*VO(2)+.59025
      A=(D+F-2.*E)/800.
      B=(E-F)/20.-140./800.*(D-2.*E+F)
      C=10.*F-15.*E+6.*D
      ETA1=A*VO(1)*VO(1)+B*VO(1)+C
      CU=.937
      D=.76-(VO(2)-15.)*.004
      F=.735-(VO(2)-15.)*.005
      E=.745-(VO(2)-15.)*.005
      A=(D+F-2.*E)/800.
      B=(E-F)/20.-140./800.*(D+F-2.*E)
      C=10.*F-15.*E+6.*D
      ETA2=A*VO(1)*VO(1)+B*VO(1)+C
C     CALCULATION OF INLET DRAG COEFFICIENT FOR 2.5 ASPECT
C     RATIO INLETS
      F=.11
      E=.0006*VO(2)+.084
      D=.092
      A=(D+F-2.*E)/800.
      B=(E-F)/20.-140./800.*(D-2.*E+F)
      C=10.*F-15.*E+6.*D
      CDIN1=A*VO(1)*VO(1)+B*VO(1)+C
      CWIN=6.0
      RETURN
   30 CONTINUE
      D=.000225*VO(2)*VO(2)-.0085*VO(2)+.611875
```

```
E=.00006*VC(2)*VC(2)-.0022*VC(2)+.5855
F=.594
A=(D+F-2.*E)/800.
B=(E-F)/20.-140./800.*(D+F-2.*E)
C=10.*F-15.*E+6.*D
ETA1=A*VC(1)*VO(1)+B*VC(1)+C
ETA2=.75-.004*(VO(2)-15.)
E=.138
D=.000065*VO(2)*VO(2)-.0022*VO(2)+.120375
F=.215
A=(D+F-2.*E)/800.
B=(E-F)/20.-140./800.*(D+F-2.*E)
C=10.*F-15.*E+6.*D
CDIN1=A*VC(1)*VC(1)+B*VC(1)+C
CWIN=4.7
CU=.984
RETURN
END
```

```
      SUBROUTINE PUMP
      COMMON/POUT/PRC1,SSS2,RPM2
      COMMON/INDEX/IAR,IPRINT,IREAD,IENGN,NSTG,LAST
      COMMON/PARIN/ETA1,ETA2,CU,CDIN1
      COMMON/VELOC/VO(2),VJVO(2)
      COMMON/PUMA/CAC,COR1,COR2
      COMMON/SHIP/DISP,RANGE,DRAG(2)
      COMMON/COEF/DCOF,ENETA,AJET
      COMMON/HEAD/HA,HEW,HEP,Q(2),HE
      COMMON/PL4 /RTIP,RPM(2),ETAP(2),DRAT,HSV(2),HPP(2)
      COMMON/PERFO/PERF(5,12),WTRAT,XNGT
      COMMON/CONST/PI,G,RHOW,XK
      DIMENSION QQ(2),ETAOA(2),CDIN(2),PC(2,3),PCA(2,3),VTIP(2),PRC(2)
      DATA PC/-3.0,-1.7,4.8,3.42,-0.8,-0.72/
      DATA PCA/-1.0,-1.7,1.0,3.42,1.0,-0.72/
      ETAP(1)=0.0
      ETAP(2)=0.0
C     CORRECT OVERALL INTERNAL EFFICIENCY AND DRAG COEFFICIENT
C     FOR EFFECTS OF HEIGHT
      ETAOA(1)=ETA1-COR1
      ETAOA(2)=ETA2-COR2
      CDIN(1)=CDIN1
      CDIN(2)=CDIN(1)
      ENETA=ETAOA(1)*CU*CU
      DCOF=CDIN(1)
C     COMPUTE REQUIRED FLOW AND HEAD AND NPSH AT TAKEOFF(2)
C     AND CRUISE(1)
      Q(1)=DRAG(1)/(RHOW*VO(1)*(VJVO(1)-CU-CDIN(1)/2.))
      AJET=Q(1)/(VJVO(1)*VO(1))
      FACT=.5+CAC*CDIN(2)/4.
      VJVO(2)=FACT+SQRT(FACT*FACT+CAC*DRAG(2)/(RHOW*AJET*VO(2)*VO(2)))
      Q(2)=AJET*VJVO(2)*VO(2)
      C=CU*CU
      DO 2 I=1,2
      IF(I.EQ.2) C=1.0
      QQ(I)=Q(I)/XNGT
```

```
      HPP(I)=HEP-HE+((VJVO(I)*VJVO(I)-C*ETAOA(I))*VO(I)*VO(I))/(2.*G)
      HSV(I)=HA-HEP+HE+(C*ETACA(I)*VO(I)*VO(I))/(2.*G)
    2 CONTINUE
      LAST=1
      DRAT=.3
      PHI=0.15
      QX=QQ(1)/QQ(2)
      HX=HPP(1)/HPP(2)
      VTIP(2)=200.
      XKEFF=10.
      ISTEER=0
      ICONT=0
   40 CONTINUE
      RTIP=SQRT(QQ(2)/(PI*VTIP(2)*PHI*(1.-DRAT*DRAT)))
      RPM(2)=VTIP(2)*60./(RTIP*2.*PI)
      SSS=RPM(2)*QQ(2)**.5/HSV(2)**.75
      IF(ISTEER.GT.0) GO TO 51
      IF(SSS.LT.755.) GO TO 50
      VTIP(2)=VTIP(2)-1.
      GO TO 40
   50 CONTINUE
      ISTEER=10
   51 CONTINUE
      SHI=G*HPP(2)/(VTIP(2)*VTIP(2))
      IF(SHI.GT.1.01) GO TO 36
   52 NSTG=2
      IF(SHI.LE.0.41) NSTG=1
      IF(SHI.GT.0.71)NSTG=3
      IF(NSTG-2)60,70,70
   60 IF(ICONT-10)61,65,61
   61 ICONT=10
      CA= PC(1,2)/PC(1,3)*.5
      CB=PC(1,1)/PC(1,3)
      RX=-CA*QX-SQRT(QX*QX*(CA*CA-CB)+HX/PC(1,3))
   65 CONTINUE
      ETAP(2)=1.0-((3.666/(2.*RTIP))**.165*(1.-.915))
```

```
      PRC(2)=2.0*.98*.98*ETAP(2)*(VJVO(2)-1.-CDIN(2)*CAC/2.+CDIN(2)*CAC/
     1(2.*VO(2)))/(VJVO(2)*VJVO(2)-ETAOA(2)+2.*(HEP-HE)*G/(VO(2)*VO(2)))
      IF(DRAG(2)*VO(2)*CAC+CAC*CDIN(2)*DRAG(2)/(2.*(VJVO(2)-1.-CAC*CDIN(
     12)/2.)).LE.550.*PRC(2)*PERF(2,IENGN)*XNGT) GO TO 75
      VTIP(2)=VTIP(2)-1.
      GO TO 40
   75 CONTINUE
      IF(ICONT.GT.11) GO TO 76
      ETAX=PC(2,1)*QX**2+PC(2,2)*QX+PC(2,3)
      IF(ETAX.LE.0.) ETAX=.001
      ETAP(1)=ETAP(2)*ETAX
   77 CONTINUE
      PRC(1)=2.*.98*.98*ETAP(1)*(VJVO(1)-CU-CDIN(1)/2.+CDIN(1)/(2.*VO(1)
     1))/(VJVO(1)*VJVO(1)-C*ETACA(1)+2.*G*(HEP-HE)/(VO(1)*VO(1)))
      IF(DRAG(1)*VO(1)+CDIN(1)*DRAG(1)/(2.*(VJVO(1)-CU-CDIN(1)/2.)).LE.
     1PERF(1,IENGN)*PRC(1)*XNCT*550.) GO TO 78
      VTIP(2)=VTIP(2)-1.
      GO TO 40
   70 CONTINUE
      IF(ICONT.GT.11) GO TO 65
      ICONT=20
      CA=PCA(1,2)/PCA(1,3)*.5
      CB=PCA(1,1)/PCA(1,3)
      RX=-CA*QX+SQRT(QX*QX*(CA*CA-CB)+HX/PCA(1,3))*(CA/ABS(CA))
      GO TO 65
   36 IF(LAST-2) 90,80,52
   76 CONTINUE
      ETAX=PCA(2,1)*QX**2+PCA(2,2)*QX+PCA(2,3)
      IF(ETAX.LE.0.) ETAX=.001
      ETAP(1)=ETAP(2)*ETAX
      GO TO 77
   78 CONTINUE
      RPM(1)=RPM(2)*RX
      VTIP(1)=RPM(1)*2.*PI*RTIP/60.
      IF(VTIP(1).LE.200.) GO TO 30
      VTIP(2)=VTIP(2)-1.0
```

```
      GO TO 40
   30 CONTINUE
      CALL WEIGHT
      IF(LAST.EQ.3) GO TO 83
      IF(XKEEP.LT.WTRAT) GO TO 80
      XKEEP=WTRAT
      LAST=2
      VTIP(2)=VTIP(2)-1.
      GO TO 40
   80 CONTINUE
      LAST=3
      VTIP(2)=VTIP(2)+1.0
      GO TO 40
   83 CONTINUE
      GO TO 99
   90 WRITE(IPRINT, 2012) VJVO(1),ETAP(2),ETAP(1)
 2012 FORMAT(5X,'THERE IS NO SOLUTION AT VJVO(1)=',3(F15.8)/////)
      WTRAT=1.0
      RETURN
   99 CONTINUE
      SSS2=SSS
      PRC1=PRC(1)
      PHI1=QQ(1)*VTIP(2)*PHI/(VTIP(1)*QQ(2))
      RPM2=RPM(2)
      XDRAG=CDIN(1)*RHOW*Q(1)*VO(1)/2.
      RESIST=DRAG(1)+XDRAG
      WRITE(IPRINT,3100)PHI1,PHI,VTIP(1),VTIP(2),QQ(1),QQ(2)
 3100 FORMAT(5X,'FLOW COEFFICIENT-CRUISE *****=',F10.4,10X,
     1'FLOW COEFFICIENT-HUMP *******=',F10.4/5X,'TIP VELOCITY-CRUISE ***
     2******=',F10.2,10X,'TIP VELOCITY-HUMP ***********=',F10.2/5X,
     3'PUMP FLOW-CRUISE ************=',F10.2,10X,'PUMP FLOW-HUMP *******
     4*******=',F10.2///)
      WRITE(IPRINT,3111) XDRAG,RESIST
 3111 FORMAT(5X,'INLET DRAG-CRUISE ***********=',F10.1,10X,'TOTAL RESIST
     1ANCE-CRUISE *****=',F10.1///)
      RETURN
```

```
      SUBROUTINE WEIGHT
      COMMON/INDEX/IAR,IPRINT,IREAD,IENGN,NSTG,LAST
      COMMON/VELOC/VO(2),VJVC(2)
      COMMON/COEF/DCOF,ENETA,AJET
      COMMON CWIN
      COMMON/SHIP/DISP,RANGE,DRAG(2)
      COMMON/HEAD/HA,HEW,HEF,Q(2),HE
      COMMON/PUM /RTIP,RPM(2),ETAP(2),DRAT,HSV(2),HPP(2)
      COMMON/PERFC/PERF(5,12),WTRAT,XNGT
      COMMON/CONST/PI,G,RHOW,XK
      COMMON/WEMA/APUP,GERAT,SHP(2)
      DIMENSION PCOEF(3,2),WT(21),DIS(21)
      DATA PCOEF/ 1.71,1.79,2.03,347.0,393.5,439.5/
   40 XXLP=PCOEF(NSTG,1)
      CW=PCOEF(NSTG,2)
      DIS=2.*RTIP
      XWD=CW*DIS**2.3*XNGT
      PLP=DIS*XXLP
      APUP=.785*DIS**2.*(1.-DRAT*DRAT)
      XWW=.523*APUP*PLP*RHOW*G*XNGT
      XWIN=CWIN*Q(1)**1.5
      XWPIP=RHOW*G*(HEP-HE)*APUP*XNGT/.707
      XWENG=PERF(5,IENGN)*XNGT
      GERAT=PERF(4,IENGN)/RPM(2)
      DO 2 I=1,2
    2 SHP(I)=RHOW*G*Q(I)*HPP(I)/(550.*XNGT*ETAP(I)*.98*.98)
      RG=SHP(2)/PERF(4,IENGN)*(GERAT+1.)**3./GERAT
      XWGR=3500.*RG/XK*XNGT
      SSS1=RPM(1)*(Q(1)/XNGT)**.5/HSV(1)**.75
      SSS1=21.2*SSS1
      CAL=DRAG(1)/DISP
      XWF=0.0
      WT(1)=0.0
      VOTERM=VO(1)+VO(1)*DCOF/2.
      ETERM=ENETA*VO(1)*VO(1)/(2.*G)-HEP+HE
      DIS(1)=DISP
```

```
      SCONT= RHOW*G*AJET/(550.*ETAP(1)*.98*.98)
      N=21
      TI=RANGE*1.689/(VC(1)*20.)
      DO 1 I=2,N
      DIS(I)=DIS(I-1)-WT(I-1)
      VJ=VOTERM/2.+SQRT(VOTERM*VOTERM/4.+CAL*DIS(I)/(RHOW*AJET))
      SHNG=SCONT*VJ*(VJ*VJ/(2.*G)-ETERM)/XNGT
      XN=0.25
      IF(SHNG.LT.0.7*PERF(1,IENGN)) XN=0.75
      SFC=PERF(3,IENGN)/((SHNG/PERF(1,IENGN))**XN)
      WT(I)=SFC*SHNG*TI*XNGT
      XWF=WT(I)+XWF
    1 CONTINUE
      WTRAT=(XWD+XWW+XWIN+XWPIP+XWENG+XWGR+XWF)/DISP
      WTOT=WTRAT*DISP
      IF(WTRAT.GT.1.0) GO TO 7
      IF(LAST.EQ.3) GO TO 4
      RETURN
    4 CONTINUE
      ETAP(1)=ETAP(1)*100.
      ETAP(2)=ETAP(2)*100.
      WRITE(IPRINT,2100) VJVC(1)
 2100 FORMAT(30X,'******    SYSTEM WEIGHTS AT VELOCITY RATIO ='F6.3,
     1'    ******')
      WRITE(IPRINT,2200) XWD,XWENG,XWGR,XWIN
 2200 FORMAT(/   14X,'PUMP DRY =',F10.2,'      ENGINE =',F10.2,'      REDU
     1CTION GEAR =',F10.2,'     INLET SYSTEM =',F10.2)
      WRITE(IPRINT,2300) XWW,XWF,XWPIP
 2300 FORMAT(13X,'PUMP WATER =',F10.2,'        FUEL =',F10.2,
     1'     ADDITIONAL WATER =',F10.2)
      WRITE(IPRINT,2400) WTOT
 2400 FORMAT(5X,'TOTAL SYSTEM WEIGHT=',F10.2///)
      WRITE(IPRINT,2500)
 2500 FORMAT(46X,'PUMP DATA')
      WRITE(IPRINT,2600) NSTG,RPM(1),ETAP(1),ETAP(2),SSS1,HSV(1)
 2600 FORMAT(5X,'NUMBER OF STAGES ************=',I10,10X,
```

```
     1'PUMP RPM-CRUISE **************=',F10.2/5X,'PUMP EFFICIENCY-CRUISE
     2******=',F10.4,10X,'PUMP EFFICIENCY-HUMP *********=',F10.4/5X,
     3'SUCTION SPEC. SPEED-CRUISE **=',F10.2,10X,'N. POS. SUCT. HEAD-CRU
     4ISE ***=',F10.2)
      WRITE(IPRINT,2610) HPP(1),HPP(2),DIS,PLP
 2610 FORMAT(5X,'PUMP HEAD-CRUISE **************=',F10.2,10X,
     1'PUMP HEAD-HUMP ****************=',F10.2/5X,'PUMP INLET DIAMETER ***
     2******=',F10.4,10X,'PUMP LENGTH *******************=',F10.4)
      RETURN
    7 WTRAT=1.0
      LAST=3
      WRITE(IPRINT,2010) VJVC(1),WTOT
 2010 FORMAT(5X,'SYSTEM TOO HEAVY VJVO=',F5.3,5X 'WEIGHT=',F10.1)
      RETURN
      END
```

```
C       SAMPLE INPUT
C       ENGINE DATA
2220.      2840.      .59        14500.     1050.
 2850.     3060.      .55         14500.     1050.
2800.      3510.      .63        1500.      3200.
 2800.     3510.      .63         1000.     3300.
 3320.     4250.       .49       3110.      2800.
 4100.     5300.      .47        3110.      2800.
 2220.     2340.      .79        9000.      1010.
 12500.    14000.     .575       5500.      7500.
 22200.    22500.     .41         3400.      10500.
 19150.     24200.    .52        3600.      14200.
 21750.     26950.     .52       3600.      14200.
 27600.    34400.     .48        3600.      14200.
C       ENGINE TYPE AND INLET TYPE
    9    2    6
C       SYSTEM HEIGHTS AND ACCELERATION COEFFICIENT
 6.5        6.5          2.0        1.2
C       SHIP DATA
 80.        30.          230000.    325000.    2000.      1000.
```

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